



Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas

(H.F.R.I. Project Number 015376)

Investigation of the effects of renovations on VF structure

Deliverable D3.2 Work package 3

Funding source

“Hellenic Foundation for Research & Innovation (H.F.R.I.)
Greece 2.0
Basic Research Financing Action”

Host Organization



Democritus University of Thrace (DUTH)

Collaborating Organizations

Aristotle University of Thessaloniki (AUTH)

November 2025

The research project is implemented in the framework of H.F.R.I call “Basic research
Financing (Horizontal support of all Sciences)” under the National Recovery and Resilience
Plan “Greece 2.0” funded by the European Union – NextGenerationEU (H.F.R.I. Project Number: 015376)

Version	Date	Comments-Modifications
1	November 2025	Final Version
2		

Suggested citation:

Rousakis T., Vanian V., Fanaradelli T., Voutetaki M., Zapis A., Theodoridou I., 2025. Investigation of the effects of renovations on VF structure. Greenergy-Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas (H.F.R.I. Project Number 015376). Deliverable D3.2 Democritus University of Thrace, Xanthi.

Project Title	Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas
Acronym	GREENERGY
HFRI Project Number	015376
Call identifier	Basic Research Financing (Horizontal support for all Sciences), National Recovery and Resilience Plan (Greece 2.0) / Sub-action 2. Funding Projects in Leading-Edge Sectors – RRFQ: Basic Research Financing (Horizontal support for all Sciences)
Thematic area	ThA1. Physical Sciences, Engineering Sciences and Technology, Environment and Energy
Thematic Field	1.16 Smart Cities
Host Organization	Democritus University of Thrace
Collaborating Institutions	Aristotle University of Thessaloniki
Project starting date	13/3/2024
Project Principal Investigator	Dr. Theodoros Rousakis
Affiliation	Democritus University of Thrace / Department of Civil Engineering
Email	trousak@civil.duth.gr
Telephone	25410 79645, 461 / 6977421569
Deliverable number and title	D3.2 Investigation of the effects of renovations on VF structure
Related work package	WP3 - Digital twin model
Authors	Theodoros Rousakis, Vachan Vanian, Theodora Fanaradelli, Maristella Voutetaki, Adamantis Zapis (DUTH) Ifigeneia Theodoridou (AUTH)

Τίτλος Έργου	Ανθεκτική Αντισεισμική Ανακαίνιση Κατασκευών από Ωπλισμένο Σκυρόδεμα σε Κάθετο Δάσος
Ακρωνύμιο	GREENERGY
Αριθμός Έργου ΕΛΙΔΕΚ	015376
Δράση	Χρηματοδότηση Βασικής Έρευνας (Οριζόντια υποστήριξη όλων των Επιστημών), Εθνικό Σχέδιο Ανάκαμψης και Ανθεκτικότητας (Ελλάδα 2.0)
Θεματική Περιοχή	Υποδράση 2. Χρηματοδότηση Έργων σε Τομείς Αιχμής – ΤΑΑ: Χρηματοδότηση Βασικής Έρευνας (Οριζόντια υποστήριξη όλων των Επιστημών)
Θεματικό Πεδίο	1.16 Έξυπνες Πόλεις
Φορέας Υποδοχής	Δημοκρίτειο Πανεπιστήμιο Θράκης
Συνεργαζόμενος Φορέας	Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης
Ημερομηνία έναρξης Έργου	13/3/2024
Επιστημονικά Υπεύθυνος Έργου	Δρ. Θεόδωρος Ρουσάκης
Ίδρυμα / Τμήμα	Δημοκρίτειο Πανεπιστήμιο Θράκης / Πολιτικών Μηχανικών
Email	trousak@civil.duth.gr
Τηλέφωνα	25410 79645, 461 / 6977421569
Αριθμός και Τίτλος Παραδοτέου	D3.2 Διερεύνηση των επιπτώσεων των ανακατασκευών στη δομή ΚΔ
Σχετική Ενότητα Εργασίας	ΕΕ3 - Μοντέλο ψηφιακού διδύμου
Συγγραφείς	Θεόδωρος Ρουσάκης, Βαχάν Βανιάν, Θεοδώρα Φαναραδέλλη, Μαριστέλλα Βουτετάκη, Αδαμάντης Ζάπρης (ΔΠΘ) Ιφιγένεια Θεοδωρίδου (ΑΠΘ)

ACKNOWLEDGEMENTS

This project is carried out within the framework of the National Recovery and Resilience Plan Greece 2.0, funded by the European Union – NextGenerationEU (Implementation body HFRI).

TABLE OF CONTENTS

Acknowledgements.....	iv
Table of contents	v
List of tables	vii
List of figures	viii
ΠΕΡΙΛΗΨΗ	xxii
Summary	xxiii
1 Introduction	1
2 3D Structure Modeling	3
2.1 Infill MACRO modeling Approaches	3
2.1.1 Literature review of the relevant infill models	3
2.2 Current infill modeling	7
2.3 Mass distribution	9
2.4 Structural Component Cross-Section Definition.....	10
2.5 Constraints and Gravity Loads.....	11
2.6 ANSYS Explicit Dynamic Pushover Simulation PHase A	12
3 Implementation of the pushover on the as-built structure	17
4 Implementation of the dynamic time history (excitation) on the as-built structure.....	19
4.1 ST2::EQ0.1g Results	20
4.2 ST4::EQ0.2g Results	24
4.3 ST6::EQ0.5g Results	29
4.4 ST8::EQ0.8g Results	33
4.5 ST10::EQ1.1g Results	37
4.6 ST1::WNb0.1g Results.....	42
4.7 ST3::WNb0.2g Results.....	46
4.8 ST5::WNb0.5g Results.....	50
4.9 ST7::WNb0.8g Results.....	55
4.10 ST9::WNb1.1g Results.....	59
4.11 ST11::WNa1.1g Results.....	63
5 Implementation of the pushover time history on the renovated 3d VF structure	68
6 Implementation of the dynamic time history on the renovated 3d VF structure.....	73
6.1 ST3::EQ0.07G RESULTS	73
6.2 ST4::EQ0.1G RESULTS	77
6.3 ST6::EQ0.14G RESULTS	82
6.4 ST7::EQ0.2G RESULTS	86
6.5 ST9::EQ0.34G RESULTS	90
6.6 ST11::EQ0.5G RESULTS	94

6.7	ST13::EQ0.55G RESULTS	98
6.8	ST15::EQ0.74G RESULTS	103
6.9	ST17::EQ0.8G RESULTS	107
6.10	ST19::EQ1.1G RESULTS	111
6.11	ST21::EQ1.3G RESULTS	116
6.12	ST22::WNB1.3G(2) RESULTS.....	117
6.13	ST23::EQ1.3G(2) RESULTS.....	118
6.14	ST25::EQ1.4G RESULTS	123
6.15	ST27::EQ0.2G (2) RESULTS.....	127
6.16	ST1::WNB0.07G (WITHOUT) RESULTS	131
6.17	ST2::WNB0.07G RESULTS.....	136
6.18	ST5::WNB0.14G RESULTS.....	140
6.19	ST8::WNB0.34G RESULTS.....	144
6.20	ST10::WNB0.5G RESULTS.....	149
6.21	ST12::WNB0.55G RESULTS	153
6.22	ST14::WNB0.74G RESULTS	157
6.23	ST16::WNB0.8G RESULTS.....	162
6.24	ST18::WNB1.1G RESULTS.....	166
6.25	ST20::WNB1.3G RESULTS.....	170
6.26	ST24::WNB1.4G RESULTS.....	175
6.27	ST26::WNB0.2G (2) RESULTS.....	179
6.28	ST28::WNA0.2G RESULTS.....	183
7	Conclusion.....	188
	References	189

LIST OF TABLES

Table 1 Different macro-models for infills and their design approaches.....	6
Table 2 Mass distribution table for as built model.....	9
Table 3 Total Test Sequence protocol (11 tests).	19
Table 4 Experimental and numerical comparison pairs.....	19
Table 5 Mass distribution table for renovated model	70
Table 6 Loading sequence for the numerical model	73

LIST OF FIGURES

Figure 1 Macro models: (A) one diagonal strut model (B) multi-strut model of (Chrysostomou et al., 2002) (C) (El-Dakhakhni et al., 2003) (D) (Crisafulli & Carr, 2007) (E) (Rodrigues et al., 2010) (F) (Yekrangnia & Mohammadi, 2017) (G) (Kadysiewski & Mosalam, 2009) (H) (Donà et al., 2017) (I) (Di Trapani et al., 2018) (J) (Furtado et al., 2015) (K) (Gesualdi et al., 2020) [adapted from (Bouarroudj & Boudaoud, 2022)]	4
Figure 2 Proposed model from a) (Di Trapani et al., 2018) and b) (Pradhan & Cavaleri, 2020) adapted from (Pradhan & Cavaleri, 2020)	7
Figure 3 Summary workflow for infill parameters identification based on (Pradhan & Cavaleri, 2020)	8
Figure 4 Node positions for numerical model of as built structure	9
Figure 5 Fiber-Section Definition for as Built Specimen for a) columns b) hidden beams c) base beams and d) cantilever beams	10
Figure 6 Constraints for as built specimen	11
Figure 7 Gravity Loads applied to as built specimen	11
Figure 8 GREENERGY-1 specimen model: (a) geometry with reinforcement and (b) cross sections (adapted from (Vanian & Rousakis, 2025a))	12
Figure 9 GREENERGY-1 model generated by (a) database code and (b) manually edited inside FEM analysis. (adapted from (Vanian & Rousakis, 2025a))	13
Figure 10 GREENERGY-1 result for explicit dynamic analysis of the failure mechanism for EQ 1.1 g: (a) side view and (b) front view. (adapted from (Vanian & Rousakis, 2025a))	14
Figure 11 FRESCO database Example 1 results for out-of-plane specimen a) P-d curve b) damage visualization (adapted from (Vanian & Rousakis, 2025a))	15
Figure 12 FRESCO database Example 2 results for in-of-plane specimen and strengthening a) P-d curve b) damage visualization (adapted from (Vanian & Rousakis, 2025a))	15
Figure 13 Push over loads location for as built specimen	17
Figure 14 Pushover analysis result for the as-built structure	18
Figure 15 Seismic excitation of original Thessaloniki 1978 earthquake (ay component – Reference Excitation)	19
Figure 16 ST2 - Acceleration comparison Acc10 vs N34	20
Figure 17 ST2 - Acceleration comparison Acc10 vs N19	20
Figure 18 ST2 - Acceleration comparison Acc10 vs N18	21
Figure 19 ST2 - Acceleration comparison Acc1 vs N12	21
Figure 20 ST2 - Acceleration comparison Acc4 vs N11	21
Figure 21 ST2 - Acceleration comparison Acc7 vs N45	22
Figure 22 ST2 - Acceleration comparison Acc7 vs N46	22
Figure 23 ST2 - Acceleration comparison Acc7 vs N47	22
Figure 24 ST2 - Acceleration comparison Acc7 vs N48	23
Figure 25 ST2 - Displacement comparison W1 vs N12	23
Figure 26 ST2 - Displacement comparison W2 vs N11	23
Figure 27 ST2 - Displacement comparison W3 vs N24	24
Figure 28 ST2 - Displacement comparison W4 vs N23	24

Figure 29 ST4 - Acceleration comparison Acc10 vs N34.....	24
Figure 30 ST4 - Acceleration comparison Acc10 vs N19.....	25
Figure 31 ST4 - Acceleration comparison Acc10 vs N18.....	25
Figure 32 ST4 - Acceleration comparison Acc1 vs N12.....	25
Figure 33 ST4 - Acceleration comparison Acc4 vs N11.....	26
Figure 34 ST4 - Acceleration comparison Acc7 vs N45.....	26
Figure 35 ST4 - Acceleration comparison Acc7 vs N46.....	26
Figure 36 ST4 - Acceleration comparison Acc7 vs N47.....	27
Figure 37 ST4 - Acceleration comparison Acc7 vs N48.....	27
Figure 38 ST4 - Displacement comparison W1 vs N12.....	27
Figure 39 ST4 - Displacement comparison W2 vs N11.....	28
Figure 40 ST4 - Displacement comparison W3 vs N24.....	28
Figure 41 ST4 - Displacement comparison W4 vs N23.....	28
Figure 42 ST6 - Acceleration comparison Acc10 vs N34.....	29
Figure 43 ST6 - Acceleration comparison Acc10 vs N19.....	29
Figure 44 ST6 - Acceleration comparison Acc10 vs N18.....	29
Figure 45 ST6 - Acceleration comparison Acc1 vs N12.....	30
Figure 46 ST6 - Acceleration comparison Acc4 vs N11.....	30
Figure 47 ST6 - Acceleration comparison Acc7 vs N45.....	30
Figure 48 ST6 - Acceleration comparison Acc7 vs N46.....	31
Figure 49 ST6 - Acceleration comparison Acc7 vs N47.....	31
Figure 50 ST6 - Acceleration comparison Acc7 vs N48.....	31
Figure 51 ST6 - Displacement comparison W1 vs N12.....	32
Figure 52 ST6 - Displacement comparison W2 vs N11.....	32
Figure 53 ST6 - Displacement comparison W3 vs N24.....	32
Figure 54 ST6 - Displacement comparison W4 vs N23.....	33
Figure 55 ST8 - Acceleration comparison Acc10 vs N34.....	33
Figure 56 ST8 - Acceleration comparison Acc10 vs N19.....	33
Figure 57 ST8 - Acceleration comparison Acc10 vs N18.....	34
Figure 58 ST8 - Acceleration comparison Acc1 vs N12.....	34
Figure 59 ST8 - Acceleration comparison Acc4 vs N11.....	34
Figure 60 ST8 - Acceleration comparison Acc7 vs N45.....	35
Figure 61 ST8 - Acceleration comparison Acc7 vs N46.....	35
Figure 62 ST8 - Acceleration comparison Acc7 vs N47.....	35
Figure 63 ST8 - Acceleration comparison Acc7 vs N48.....	36
Figure 64 ST8 - Displacement comparison W1 vs N12.....	36
Figure 65 ST8 - Displacement comparison W2 vs N11.....	36

Figure 66 ST8 - Displacement comparison W3 vs N24.....	37
Figure 67 ST8 - Displacement comparison W4 vs N23.....	37
Figure 68 ST10 - Acceleration comparison Acc10 vs N34	37
Figure 69 ST10 - Acceleration comparison Acc10 vs N19	38
Figure 70 ST10 - Acceleration comparison Acc10 vs N18	38
Figure 71 ST10 - Acceleration comparison Acc1 vs N12.....	38
Figure 72 ST10 - Acceleration comparison Acc4 vs N11.....	39
Figure 73 ST10 - Acceleration comparison Acc7 vs N45.....	39
Figure 74 ST10 - Acceleration comparison Acc7 vs N46.....	39
Figure 75 ST10 - Acceleration comparison Acc7 vs N47.....	40
Figure 76 ST10 - Acceleration comparison Acc7 vs N48.....	40
Figure 77 ST10 - Displacement comparison W1 vs N12.....	40
Figure 78 ST10 - Displacement comparison W2 vs N11.....	41
Figure 79 ST10 - Displacement comparison W3 vs N24.....	41
Figure 80 ST10 - Displacement comparison W4 vs N23.....	41
Figure 81 ST1 - Acceleration comparison Acc10 vs N34.....	42
Figure 82 ST1 - Acceleration comparison Acc10 vs N19.....	42
Figure 83 ST1 - Acceleration comparison Acc10 vs N18.....	42
Figure 84 ST1 - Acceleration comparison Acc1 vs N12.....	43
Figure 85 ST1 - Acceleration comparison Acc4 vs N11	43
Figure 86 ST1 - Acceleration comparison Acc7 vs N45.....	43
Figure 87 ST1 - Acceleration comparison Acc7 vs N46.....	44
Figure 88 ST1 - Acceleration comparison Acc7 vs N47	44
Figure 89 ST1 - Acceleration comparison Acc7 vs N48.....	44
Figure 90 ST1 - Displacement comparison W1 vs N12.....	45
Figure 91 ST1 - Displacement comparison W2 vs N11	45
Figure 92 ST1 - Displacement comparison W3 vs N24.....	45
Figure 93 ST1 - Displacement comparison W4 vs N23.....	46
Figure 94 ST3 - Acceleration comparison Acc10 vs N34.....	46
Figure 95 ST3 - Acceleration comparison Acc10 vs N19.....	46
Figure 96 ST3 - Acceleration comparison Acc10 vs N18.....	47
Figure 97 ST3 - Acceleration comparison Acc1 vs N12.....	47
Figure 98 ST3 - Acceleration comparison Acc4 vs N11	47
Figure 99 ST3 - Acceleration comparison Acc7 vs N45.....	48
Figure 100 ST3 - Acceleration comparison Acc7 vs N46.....	48
Figure 101 ST3 - Acceleration comparison Acc7 vs N47.....	48
Figure 102 ST3 - Acceleration comparison Acc7 vs N48.....	49

Figure 103 ST3 - Displacement comparison W1 vs N12.....	49
Figure 104 ST3 - Displacement comparison W2 vs N11.....	49
Figure 105 ST3 - Displacement comparison W3 vs N24.....	50
Figure 106 ST3 - Displacement comparison W4 vs N23.....	50
Figure 107 ST5 - Acceleration comparison Acc10 vs N34	50
Figure 108 ST5 - Acceleration comparison Acc10 vs N19	51
Figure 109 ST5 - Acceleration comparison Acc10 vs N18	51
Figure 110 ST5 - Acceleration comparison Acc1 vs N12.....	51
Figure 111 ST5 - Acceleration comparison Acc4 vs N11.....	52
Figure 112 ST5 - Acceleration comparison Acc7 vs N45.....	52
Figure 113 ST5 – Acceleration comparison Acc7 vs N46	52
Figure 114 ST5 - Acceleration comparison Acc7 vs N47.....	53
Figure 115 ST5 - Acceleration comparison Acc7 vs N48.....	53
Figure 116 ST5 - Displacement comparison W1 vs N12.....	53
Figure 117 ST5 - Displacement comparison W2 vs N11.....	54
Figure 118 ST5 - Displacement comparison W3 vs N24.....	54
Figure 119 ST5 - Displacement comparison W4 vs N23.....	54
Figure 120 ST7 - Acceleration comparison Acc10 vs N34	55
Figure 121 ST7 - Acceleration comparison Acc10 vs N19	55
Figure 122 ST7 - Acceleration comparison Acc10 vs N18	55
Figure 123 ST7 - Acceleration comparison Acc1 vs N12.....	56
Figure 124 ST7 - Acceleration comparison Acc4 vs N11.....	56
Figure 125 ST7 - Acceleration comparison Acc7 vs N45.....	56
Figure 126 ST7 - Acceleration comparison Acc7 vs N46.....	57
Figure 127 ST7 - Acceleration comparison Acc7 vs N47.....	57
Figure 128 ST7 - Acceleration comparison Acc7 vs N48.....	57
Figure 129 ST7 - Displacement comparison W1 vs N12.....	58
Figure 130 ST7 - Displacement comparison W2 vs N11.....	58
Figure 131 ST7 - Displacement comparison W3 vs N24.....	58
Figure 132 ST7 - Displacement comparison W4 vs N23.....	59
Figure 133 ST9 - Acceleration comparison Acc10 vs N34	59
Figure 134 ST9 - Acceleration comparison Acc10 vs N19	59
Figure 135 ST9 - Acceleration comparison Acc10 vs N18	60
Figure 136 ST9 - Acceleration comparison Acc1 vs N12.....	60
Figure 137 ST9 - Acceleration comparison Acc4 vs N11.....	60
Figure 138 ST9 - Acceleration comparison Acc7 vs N45.....	61
Figure 139 ST9 - Acceleration comparison Acc7 vs N46.....	61

Figure 140 ST9 - Acceleration comparison Acc7 vs N47.....	61
Figure 141 ST9 - Acceleration comparison Acc7 vs N48.....	62
Figure 142 ST9 - Displacement comparison W1 vs N12.....	62
Figure 143 ST9 - Displacement comparison W2 vs N11.....	62
Figure 144 ST9 - Displacement comparison W3 vs N24.....	63
Figure 145 ST9 - Displacement comparison W4 vs N23.....	63
Figure 146 ST11 - Acceleration comparison Acc10 vs N34	63
Figure 147 ST11 - Acceleration comparison Acc10 vs N19	64
Figure 148 ST11 - Acceleration comparison Acc10 vs N18	64
Figure 149 ST11 - Acceleration comparison Acc1 vs N12	64
Figure 150 ST11 - Acceleration comparison Acc4 vs N11	65
Figure 151 ST11 - Acceleration comparison Acc7 vs N45	65
Figure 152 ST11 - Acceleration comparison Acc7 vs N46	65
Figure 153 ST11 - Acceleration comparison Acc7 vs N47	66
Figure 154 ST11 - Acceleration comparison Acc7 vs N48	66
Figure 155 ST11 - Displacement comparison W1 vs N12.....	66
Figure 156 ST11 - Displacement comparison W2 vs N11.....	67
Figure 157 ST11 - Displacement comparison W3 vs N24.....	67
Figure 158 ST11 - Displacement comparison W4 vs N23.....	67
Figure 159 Detailed 3D CAD model for the GREENERGY Phase B a) and detailed mathematical twin model b).....	68
Figure 160 Push over loads location for renovated specimen	71
Figure 161 Pushover analysis result for the renovated structure.....	72
Figure 162 ST3 - Acceleration comparison Acc10 vs N34	73
Figure 163 ST3 - Acceleration comparison Acc10 vs N19	74
Figure 164 ST3 - Acceleration comparison Acc10 vs N18	74
Figure 165 ST3 - Acceleration comparison Acc1 vs N12.....	74
Figure 166 ST3 - Acceleration comparison Acc4 vs N11.....	75
Figure 167 ST3 - Acceleration comparison Acc7 vs N45.....	75
Figure 168 ST3 - Acceleration comparison Acc7 vs N46.....	75
Figure 169 ST3 - Acceleration comparison Acc7 vs N47.....	76
Figure 170 ST3 - Acceleration comparison Acc7 vs N48.....	76
Figure 171 ST3 - Displacement comparison W1 vs N12.....	76
Figure 172 ST3 - Displacement comparison W2 vs N11.....	77
Figure 173 ST3 - Displacement comparison W3 vs N24.....	77
Figure 174 ST3 - Displacement comparison W4 vs N23.....	77
Figure 175 ST4 - Acceleration comparison Acc10 vs N34	78
Figure 176 ST4 - Acceleration comparison Acc10 vs N19	78

Figure 177 ST4 - Acceleration comparison Acc10 vs N18	78
Figure 178 ST4 - Acceleration comparison Acc1 vs N12.....	79
Figure 179 ST4 - Acceleration comparison Acc4 vs N11.....	79
Figure 180 ST4 - Acceleration comparison Acc7 vs N45.....	79
Figure 181 ST4 - Acceleration comparison Acc7 vs N46.....	80
Figure 182 ST4 - Acceleration comparison Acc7 vs N47.....	80
Figure 183 ST4 - Acceleration comparison Acc7 vs N48.....	80
Figure 184 ST4 - Displacement comparison W1 vs N12.....	81
Figure 185 ST4 - Displacement comparison W2 vs N11.....	81
Figure 186 ST4 - Displacement comparison W4 vs N23.....	81
Figure 187 ST4 - Displacement comparison W3 vs N24.....	82
Figure 188 ST6 - Acceleration comparison Acc10 vs N34	82
Figure 189 ST6 - Acceleration comparison Acc10 vs N19	83
Figure 190 ST6 - Acceleration comparison Acc10 vs N18	83
Figure 191 ST6 - Acceleration comparison Acc1 vs N12.....	83
Figure 192 ST6 - Acceleration comparison Acc4 vs N11.....	83
Figure 193 ST6 - Acceleration comparison Acc7 vs N45.....	84
Figure 194 ST6 - Acceleration comparison Acc7 vs N46.....	84
Figure 195 ST6 - Acceleration comparison Acc7 vs N47.....	84
Figure 196 ST6 - Acceleration comparison Acc7 vs N48.....	85
Figure 197 ST6 - Displacement comparison W1 vs N12.....	85
Figure 198 ST6 - Displacement comparison W2 vs N11.....	85
Figure 199 ST6 - Displacement comparison W3 vs N24.....	86
Figure 200 ST6 - Displacement comparison W4 vs N23.....	86
Figure 201 ST7 - Acceleration comparison Acc10 vs N34	86
Figure 202 ST7 - Acceleration comparison Acc10 vs N19	87
Figure 203 ST7 - Acceleration comparison Acc10 vs N18	87
Figure 204 ST7 - Acceleration comparison Acc1 vs N12.....	87
Figure 205 ST7 - Acceleration comparison Acc4 vs N11.....	88
Figure 206 ST7 - Acceleration comparison Acc7 vs N45.....	88
Figure 207 ST7 - Acceleration comparison Acc7 vs N46	88
Figure 208 ST7 - Acceleration comparison Acc7 vs N47.....	89
Figure 209 ST7 - Acceleration comparison Acc7 vs N48.....	89
Figure 210 ST7 - Displacement comparison W1 vs N12.....	89
Figure 211 ST7 - Displacement comparison W2 vs N11.....	90
Figure 212 ST7 - Displacement comparison W3 vs N24.....	90
Figure 213 ST7 - Displacement comparison W4 vs N23.....	90

Figure 214 ST9 - Acceleration comparison Acc10 vs N34	91
Figure 215 ST9 - Acceleration comparison Acc1 vs N12.....	91
Figure 216 ST9 - Acceleration comparison Acc4 vs N11.....	91
Figure 217 ST9 - Acceleration comparison Acc7 vs N45.....	92
Figure 218 ST9 - Acceleration comparison Acc7 vs N46.....	92
Figure 219 ST9 - Acceleration comparison Acc7 vs N47.....	92
Figure 220 ST9 - Acceleration comparison Acc7 vs N48.....	93
Figure 221 ST9 - Displacement comparison W1 vs N12.....	93
Figure 222 ST9 - Displacement comparison W2 vs N11.....	93
Figure 223 ST9 - Displacement comparison W3 vs N24.....	94
Figure 224 ST9 - Displacement comparison W4 vs N23.....	94
Figure 225 ST11 - Acceleration comparison Acc10 vs N34	94
Figure 226 ST11 - Acceleration comparison Acc10 vs N19	95
Figure 227 ST11 - Acceleration comparison Acc10 vs N18	95
Figure 228 ST11 - Acceleration comparison Acc1 vs N12	95
Figure 229 ST11 - Acceleration comparison Acc4 vs N11	96
Figure 230 ST11 - Acceleration comparison Acc7 vs N45	96
Figure 231 ST11 - Acceleration comparison Acc7 vs N46	96
Figure 232 ST11 - Acceleration comparison Acc7 vs N47	97
Figure 233 ST11 - Acceleration comparison Acc7 vs N48	97
Figure 234 ST11 - Displacement comparison W1 vs N12.....	97
Figure 235 ST11 - Displacement comparison W2 vs N11.....	98
Figure 236 ST11 - Displacement comparison W3 vs N24.....	98
Figure 237 ST11 - Displacement comparison W4 vs N23.....	98
Figure 238 ST13 - Acceleration comparison Acc10 vs N34	99
Figure 239 ST13 - Acceleration comparison Acc10 vs N19	99
Figure 240 ST13 - Acceleration comparison Acc10 vs N18	99
Figure 241 ST13 - Acceleration comparison Acc1 vs N12	100
Figure 242 ST13 - Acceleration comparison Acc4 vs N11	100
Figure 243 ST13 - Acceleration comparison Acc7 vs N45	100
Figure 244 ST13 - Acceleration comparison Acc7 vs N46	101
Figure 245 ST13 - Acceleration comparison Acc7 vs N47	101
Figure 246 ST13 - Acceleration comparison Acc7 vs N48	101
Figure 247 ST13 - Displacement comparison W1 vs N12.....	102
Figure 248 ST13 - Displacement comparison W2 vs N11.....	102
Figure 249 ST13 - Displacement comparison W3 vs N24.....	102
Figure 250 ST13 - Displacement comparison W4 vs N23.....	103

Figure 251 ST15 - Acceleration comparison Acc10 vs N34	103
Figure 252 ST15 - Acceleration comparison Acc10 vs N19	103
Figure 253 ST15 - Acceleration comparison Acc10 vs N18	104
Figure 254 ST15 - Acceleration comparison Acc1 vs N12	104
Figure 255 ST15 - Acceleration comparison Acc4 vs N11	104
Figure 256 ST15 - Acceleration comparison Acc7 vs N45	105
Figure 257 ST15 - Acceleration comparison Acc7 vs N46	105
Figure 258 ST15 - Acceleration comparison Acc7 vs N47	105
Figure 259 ST15 - Acceleration comparison Acc7 vs N48	106
Figure 260 ST15 - Displacement comparison W1 vs N12.....	106
Figure 261 ST15 - Displacement comparison W2 vs N11.....	106
Figure 262 ST15 - Displacement comparison W3 vs N24.....	107
Figure 263 ST15 - Displacement comparison W4 vs N23.....	107
Figure 264 ST17 - Acceleration comparison Acc10 vs N34	107
Figure 265 ST17 - Acceleration comparison Acc10 vs N19	108
Figure 266 ST17 - Acceleration comparison Acc10 vs N18	108
Figure 267 ST17 - Acceleration comparison Acc1 vs N12	108
Figure 268 ST17 - Acceleration comparison Acc4 vs N11	109
Figure 269 ST17 - Acceleration comparison Acc7 vs N45	109
Figure 270 ST17 - Acceleration comparison Acc7 vs N46	109
Figure 271 ST17 - Acceleration comparison Acc7 vs N47	110
Figure 272 ST17 - Acceleration comparison Acc7 vs N48	110
Figure 273 ST17 - Displacement comparison W1 vs N12.....	110
Figure 274 ST17 - Displacement comparison W2 vs N11.....	111
Figure 275 ST17 - Displacement comparison W3 vs N24.....	111
Figure 276 ST17 - Displacement comparison W4 vs N23.....	111
Figure 277 ST19 - Acceleration comparison Acc10 vs N34	112
Figure 278 ST19 - Acceleration comparison Acc10 vs N19	112
Figure 279 ST19 - Acceleration comparison Acc10 vs N18	112
Figure 280 ST19 - Acceleration comparison Acc1 vs N12	113
Figure 281 ST19 - Acceleration comparison Acc4 vs N11	113
Figure 282 ST19 - Acceleration comparison Acc7 vs N45	113
Figure 283 ST19 - Acceleration comparison Acc7 vs N46	114
Figure 284 ST19 - Acceleration comparison Acc7 vs N47	114
Figure 285 ST19 - Acceleration comparison Acc7 vs N48	114
Figure 286 ST19 - Displacement comparison W1 vs N12.....	115
Figure 287 ST19 - Displacement comparison W2 vs N11.....	115

Figure 288 ST19 - Displacement comparison W3 vs N24.....	115
Figure 289 ST19 - Displacement comparison W4 vs N23.....	116
Figure 290 ST21 - Displacement comparison W1 vs N12.....	116
Figure 291 ST21 - Displacement comparison W2 vs N11.....	116
Figure 292 ST21 - Displacement comparison W3 vs N24.....	117
Figure 293 ST21 - Displacement comparison W4 vs N23.....	117
Figure 294 ST22 - Displacement comparison W1 vs N12.....	117
Figure 295 ST22 - Displacement comparison W2 vs N11.....	118
Figure 296 ST22 - Displacement comparison W3 vs N24.....	118
Figure 297 ST22 - Displacement comparison W4 vs N23.....	118
Figure 298 ST23 - Acceleration comparison Acc10 vs N34	119
Figure 299 ST23 - Acceleration comparison Acc10 vs N19	119
Figure 300 ST23 - Acceleration comparison Acc10 vs N18	119
Figure 301 ST23 - Acceleration comparison Acc1 vs N12	120
Figure 302 ST23 - Acceleration comparison Acc4 vs N11	120
Figure 303 ST23 - Acceleration comparison Acc7 vs N45	120
Figure 304 ST23 - Acceleration comparison Acc7 vs N46	121
Figure 305 ST23 - Acceleration comparison Acc7 vs N47	121
Figure 306 ST23 - Acceleration comparison Acc7 vs N48	121
Figure 307 ST23 - Displacement comparison W1 vs N12.....	122
Figure 308 ST23 - Displacement comparison W2 vs N11.....	122
Figure 309 ST23 - Displacement comparison W3 vs N24.....	122
Figure 310 ST23 - Displacement comparison W4 vs N23.....	123
Figure 311 ST25 - Acceleration comparison Acc10 vs N34	123
Figure 312 ST25 - Acceleration comparison Acc10 vs N19	123
Figure 313 ST25 - Acceleration comparison Acc10 vs N18	124
Figure 314 ST25 - Acceleration comparison Acc1 vs N12	124
Figure 315 ST25 - Acceleration comparison Acc4 vs N11	124
Figure 316 ST25 - Acceleration comparison Acc7 vs N45	125
Figure 317 ST25 - Acceleration comparison Acc7 vs N46	125
Figure 318 ST25 - Acceleration comparison Acc7 vs N47	125
Figure 319 ST25 - Acceleration comparison Acc7 vs N48	126
Figure 320 ST25 - Displacement comparison W1 vs N12.....	126
Figure 321 ST25 - Displacement comparison W2 vs N11.....	126
Figure 322 ST25 - Displacement comparison W3 vs N24.....	127
Figure 323 ST25 - Displacement comparison W4 vs N23.....	127
Figure 324 ST27 - Acceleration comparison Acc10 vs N34	127

Figure 325 ST27 - Acceleration comparison Acc10 vs N19	128
Figure 326 ST27 - Acceleration comparison Acc10 vs N18	128
Figure 327 ST27 - Acceleration comparison Acc1 vs N12	128
Figure 328 ST27 - Acceleration comparison Acc4 vs N11	129
Figure 329 ST27 - Acceleration comparison Acc7 vs N45	129
Figure 330 ST27 - Acceleration comparison Acc7 vs N46	129
Figure 331 ST27 - Acceleration comparison Acc7 vs N47	130
Figure 332 ST27 - Acceleration comparison Acc7 vs N48	130
Figure 333 ST27 - Displacement comparison W1 vs N12.....	130
Figure 334 ST27 - Displacement comparison W2 vs N11.....	131
Figure 335 ST27 - Displacement comparison W3 vs N24.....	131
Figure 336 ST27 - Displacement comparison W4 vs N23.....	131
Figure 337 ST1 - Acceleration comparison Acc10 vs N34	132
Figure 338 ST1 - Acceleration comparison Acc10 vs N19	132
Figure 339 ST1 - Acceleration comparison Acc10 vs N18	132
Figure 340 ST1 - Acceleration comparison Acc1 vs N12.....	133
Figure 341 ST1 - Acceleration comparison Acc4 vs N11.....	133
Figure 342 ST1 - Acceleration comparison Acc7 vs N45.....	133
Figure 343 ST1 - Acceleration comparison Acc7 vs N46.....	134
Figure 344 ST1 - Acceleration comparison Acc7 vs N47.....	134
Figure 345 ST1 - Acceleration comparison Acc7 vs N48.....	134
Figure 346 ST1 - Displacement comparison W1 vs N12.....	135
Figure 347 ST1 - Displacement comparison W2 vs N11.....	135
Figure 348 ST1 - Displacement comparison W3 vs N24.....	135
Figure 349 ST1 - Displacement comparison W4 vs N23.....	136
Figure 350 ST2 - Acceleration comparison Acc10 vs N34	136
Figure 351 ST2 - Acceleration comparison Acc10 vs N19	136
Figure 352 ST2 - Acceleration comparison Acc10 vs N18	137
Figure 353 ST2 - Acceleration comparison Acc1 vs N12.....	137
Figure 354 ST2 - Acceleration comparison Acc4 vs N11.....	137
Figure 355 ST2 - Acceleration comparison Acc7 vs N45.....	138
Figure 356 ST2 - Acceleration comparison Acc7 vs N46.....	138
Figure 357 ST2 - Acceleration comparison Acc7 vs N47.....	138
Figure 358 ST2 - Acceleration comparison Acc7 vs N48.....	139
Figure 359 ST2 - Displacement comparison W1 vs N12.....	139
Figure 360 ST2 - Displacement comparison W2 vs N11.....	139
Figure 361 ST2 - Displacement comparison W3 vs N24.....	140

Figure 362 ST2 - Displacement comparison W4 vs N23.....	140
Figure 363 ST5 - Acceleration comparison Acc10 vs N34	140
Figure 364 ST5 - Acceleration comparison Acc10 vs N19	141
Figure 365 ST5 - Acceleration comparison Acc10 vs N18	141
Figure 366 ST5 - Acceleration comparison Acc1 vs N12.....	141
Figure 367 ST5 - Acceleration comparison Acc4 vs N11.....	142
Figure 368 ST5 - Acceleration comparison Acc7 vs N45.....	142
Figure 369 ST5 - Acceleration comparison Acc7 vs N46.....	142
Figure 370 ST5 - Acceleration comparison Acc7 vs N47.....	143
Figure 371 ST5 - Acceleration comparison Acc7 vs N48.....	143
Figure 372 ST5 - Displacement comparison W1 vs N12.....	143
Figure 373 ST5 - Displacement comparison W2 vs N11.....	144
Figure 374 ST5 - Displacement comparison W3 vs N24.....	144
Figure 375 ST5 - Displacement comparison W4 vs N23.....	144
Figure 376 ST8 - Acceleration comparison Acc10 vs N34	145
Figure 377 ST8 - Acceleration comparison Acc10 vs N19	145
Figure 378 ST8 - Acceleration comparison Acc10 vs N18	145
Figure 379 ST8 - Acceleration comparison Acc1 vs N12.....	146
Figure 380 ST8 - Acceleration comparison Acc4 vs N11.....	146
Figure 381 ST8 - Acceleration comparison Acc7 vs N45.....	146
Figure 382 ST8 - Acceleration comparison Acc7 vs N46.....	147
Figure 383 ST8 - Acceleration comparison Acc7 vs N47.....	147
Figure 384 ST8 - Acceleration comparison Acc7 vs N48.....	147
Figure 385 ST8 - Displacement comparison W1 vs N12.....	148
Figure 386 ST8 - Displacement comparison W2 vs N11.....	148
Figure 387 ST8 - Displacement comparison W3 vs N24.....	148
Figure 388 ST8 - Displacement comparison W4 vs N23.....	149
Figure 389 ST10 - Acceleration comparison Acc10 vs N34	149
Figure 390 ST10 - Acceleration comparison Acc10 vs N19	149
Figure 391 ST10 - Acceleration comparison Acc10 vs N18	150
Figure 392 ST10 - Acceleration comparison Acc1 vs N12	150
Figure 393 ST10 - Acceleration comparison Acc4 vs N11	150
Figure 394 ST10 - Acceleration comparison Acc7 vs N45	151
Figure 395 ST10 - Acceleration comparison Acc7 vs N46	151
Figure 396 ST10 - Acceleration comparison Acc7 vs N47	151
Figure 397 ST10 - Acceleration comparison Acc7 vs N48	152
Figure 398 ST10 - Displacement comparison W1 vs N12.....	152

Figure 399 ST10 - Displacement comparison W2 vs N11.....	152
Figure 400 ST10 - Displacement comparison W3 vs N24.....	153
Figure 401 ST10 - Displacement comparison W4 vs N23.....	153
Figure 402 ST12 - Acceleration comparison Acc10 vs N34	153
Figure 403 ST12 - Acceleration comparison Acc10 vs N19	154
Figure 404 ST12 - Acceleration comparison Acc10 vs N18	154
Figure 405 ST12 - Acceleration comparison Acc1 vs N12	154
Figure 406 ST12 - Acceleration comparison Acc4 vs N11	155
Figure 407 ST12 - Acceleration comparison Acc7 vs N45	155
Figure 408 ST12 - Acceleration comparison Acc7 vs N46	155
Figure 409 ST12 - Acceleration comparison Acc7 vs N47	156
Figure 410 ST12 - Acceleration comparison Acc7 vs N48	156
Figure 411 ST12 - Displacement comparison W1 vs N12.....	156
Figure 412 ST12 - Displacement comparison W2 vs N11.....	157
Figure 413 ST12 - Displacement comparison W3 vs N24.....	157
Figure 414 ST12 - Displacement comparison W4 vs N23.....	157
Figure 415 ST14 - Acceleration comparison Acc10 vs N34	158
Figure 416 ST14 - Acceleration comparison Acc10 vs N19	158
Figure 417 ST14 - Acceleration comparison Acc10 vs N18	158
Figure 418 ST14 - Acceleration comparison Acc1 vs N12	159
Figure 419 ST14 - Acceleration comparison Acc4 vs N11	159
Figure 420 ST14 - Acceleration comparison Acc7 vs N45	159
Figure 421 ST14 - Acceleration comparison Acc7 vs N46	160
Figure 422 ST14 - Acceleration comparison Acc7 vs N47	160
Figure 423 ST14 - Acceleration comparison Acc7 vs N48	160
Figure 424 ST14 - Displacement comparison W1 vs N12.....	161
Figure 425 ST14 - Displacement comparison W2 vs N11.....	161
Figure 426 ST14 - Displacement comparison W3 vs N24.....	161
Figure 427 ST14 - Displacement comparison W4 vs N23.....	162
Figure 428 ST16 - Acceleration comparison Acc10 vs N34	162
Figure 429 ST16 - Acceleration comparison Acc10 vs N19	162
Figure 430 ST16 - Acceleration comparison Acc10 vs N18	163
Figure 431 ST16 - Acceleration comparison Acc1 vs N12	163
Figure 432 ST16 - Acceleration comparison Acc4 vs N11	163
Figure 433 ST16 - Acceleration comparison Acc7 vs N45	164
Figure 434 ST16 - Acceleration comparison Acc7 vs N46	164
Figure 435 ST16 - Acceleration comparison Acc7 vs N47	164

Figure 436 ST16 - Acceleration comparison Acc7 vs N48	165
Figure 437 ST16 - Displacement comparison W1 vs N12.....	165
Figure 438 ST16 - Displacement comparison W2 vs N11.....	165
Figure 439 ST16 - Displacement comparison W3 vs N24.....	166
Figure 440 ST16 - Displacement comparison W4 vs N23.....	166
Figure 441 ST18 - Acceleration comparison Acc10 vs N34	166
Figure 442 ST18 - Acceleration comparison Acc10 vs N19	167
Figure 443 ST18 - Acceleration comparison Acc10 vs N18	167
Figure 444 ST18 - Acceleration comparison Acc1 vs N12	167
Figure 445 ST18 - Acceleration comparison Acc4 vs N11	168
Figure 446 ST18 - Acceleration comparison Acc7 vs N45	168
Figure 447 ST18 - Acceleration comparison Acc7 vs N46	168
Figure 448 ST18 - Acceleration comparison Acc7 vs N47	169
Figure 449 ST18 - Acceleration comparison Acc7 vs N48	169
Figure 450 ST18 - Displacement comparison W1 vs N12.....	169
Figure 451 ST18 - Displacement comparison W2 vs N11.....	170
Figure 452 ST18 - Displacement comparison W3 vs N24.....	170
Figure 453 ST18 - Displacement comparison W4 vs N23.....	170
Figure 454 ST20 - Acceleration comparison Acc10 vs N34	171
Figure 455 ST20 - Acceleration comparison Acc10 vs N19	171
Figure 456 ST20 - Acceleration comparison Acc10 vs N18	171
Figure 457 ST20 - Acceleration comparison Acc1 vs N12	172
Figure 458 ST20 - Acceleration comparison Acc4 vs N11	172
Figure 459 ST20 - Acceleration comparison Acc7 vs N45	172
Figure 460 ST20 - Acceleration comparison Acc7 vs N46	173
Figure 461 ST20 - Acceleration comparison Acc7 vs N47	173
Figure 462 ST20 - Acceleration comparison Acc7 vs N48	173
Figure 463 ST20 - Displacement comparison W1 vs N12.....	174
Figure 464 ST20 - Displacement comparison W2 vs N11.....	174
Figure 465 ST20 - Displacement comparison W3 vs N24.....	174
Figure 466 ST20 - Displacement comparison W4 vs N23.....	175
Figure 467 ST24 - Acceleration comparison Acc10 vs N34	175
Figure 468 ST24 - Acceleration comparison Acc10 vs N19	175
Figure 469 ST24 - Acceleration comparison Acc10 vs N18	176
Figure 470 ST24 - Acceleration comparison Acc1 vs N12	176
Figure 471 ST24 - Acceleration comparison Acc4 vs N11	177
Figure 472 ST24 - Acceleration comparison Acc7 vs N45	177

Figure 473 ST24 - Acceleration comparison Acc7 vs N46	177
Figure 474 ST24 - Acceleration comparison Acc7 vs N47	177
Figure 475 ST24 - Acceleration comparison Acc7 vs N48	178
Figure 476 ST24 - Displacement comparison W1 vs N12.....	178
Figure 477 ST24 - Displacement comparison W2 vs N11.....	178
Figure 478 ST24 - Displacement comparison W3 vs N24.....	179
Figure 479 ST24 - Displacement comparison W4 vs N23.....	179
Figure 480 ST26 - Acceleration comparison Acc10 vs N34	179
Figure 481 ST26 - Acceleration comparison Acc10 vs N19	180
Figure 482 ST26 - Acceleration comparison Acc10 vs N18	180
Figure 483 ST26 - Acceleration comparison Acc1 vs N12	180
Figure 484 ST26 - Acceleration comparison Acc4 vs N11	181
Figure 485 ST26 - Acceleration comparison Acc7 vs N45	181
Figure 486 ST26 - Acceleration comparison Acc7 vs N46	181
Figure 487 ST26 - Acceleration comparison Acc7 vs N47	182
Figure 488 ST26 - Acceleration comparison Acc7 vs N48	182
Figure 489 ST26 - Displacement comparison W1 vs N12.....	182
Figure 490 ST26 - Displacement comparison W2 vs N11.....	183
Figure 491 ST26 - Displacement comparison W3 vs N24.....	183
Figure 492 ST26 - Displacement comparison W4 vs N23.....	183
Figure 493 ST28 - Acceleration comparison Acc10 vs N34	184
Figure 494 ST28 - Acceleration comparison Acc10 vs N19	184
Figure 495 ST28 - Acceleration comparison Acc10 vs N18	184
Figure 496 ST28 - Acceleration comparison Acc1 vs N12	185
Figure 497 ST28 - Acceleration comparison Acc4 vs N11	185
Figure 498 ST28 - Acceleration comparison Acc7 vs N45	185
Figure 499 ST28 - Acceleration comparison Acc7 vs N46	186
Figure 500 ST28 - Acceleration comparison Acc7 vs N47	186
Figure 501 ST28 - Acceleration comparison Acc7 vs N48	186
Figure 502 ST28 - Displacement comparison W1 vs N12.....	187
Figure 503 ST28 - Displacement comparison W2 vs N11.....	187
Figure 504 ST28 - Displacement comparison W3 vs N24.....	187
Figure 505 ST28 - Displacement comparison W4 vs N23.....	188

ΠΕΡΙΛΗΨΗ

Στην παρούσα έκθεση παραδοτέου, παρουσιάζεται η λεπτομερής ανάπτυξη του μαθηματικού μοντέλου για το ψηφιακό δίδυμο (digital twin model) με το προηγμένο Structural API (Application Programming Interface) του ReplicaXLite, το οποίο αναπτύχθηκε με την βοήθεια των βιβλιοθηκών ανοιχτού κώδικα πεπερασμένων στοιχείων OpenSeesPy και opstool, μεταξύ άλλων. Η προσομοίωση ολοκληρώθηκε πλήρως στο περιβάλλον προγραμματισμού ανοιχτού κώδικα Python 3 με το Ολοκληρωμένο Περιβάλλον Ανάπτυξης (Integrated Development Environment - IDE) ανοιχτού κώδικα Visual Studio Code. Το αναπτυχθέν προσομοίωμα (ReplicaXLite Structural API) αφορά τόσο την πρώτη φάση των δοκιμών όσο και τη δεύτερη φάση με τις δομικές και πράσινες επεμβάσεις, λαμβάνοντας υπόψη τα διαφορετικά στάδια επεμβάσεων και πρόσθετων μαζών. Για την πρόσθετη τεκμηρίωση της μέγιστης τέμνουσας ικανότητας βάσης στην αναμενόμενη μέγιστη μετακίνηση κορυφής, αξιοποιήθηκε κατάλληλο προσομοίωμα τρισδιάστατων πεπερασμένων στοιχείων στο ANSYS Explicit Dynamics και αναπτύχθηκε η βάση δεδομένων FRESCO. Οι παραπάνω αναλυτικές διερευνήσεις με τρισδιάστατα πεπερασμένα στοιχεία σε συνδυασμό με τα πειραματικά αποτελέσματα, οδήγησαν στην βελτιστοποίηση της προσομοίωσης με το ReplicaXLite Structural API. Τα προσομοιώματα δοκιμάστηκαν τόσο με Υπερωθητική Ανάλυση (Pushover Analysis) όσο και με Δυναμική Ανάλυση Χρονοϊστορίας (Dynamic Time History Analysis) με το ReplicaXLite Structural API. Τα αποτελέσματα από τα προσομοιώματα συγκρίθηκαν με τα πειραματικά αποτελέσματα στους αντίστοιχους κόμβους, με τα αποτελέσματα από τα όργανα μέτρησης επιταχύνσεων και μετακινήσεων, κοινά για την πρώτη και τη δεύτερη φάση.

Λέξεις-κλειδιά: μοντέλο ψηφιακού διδύμου, αναλυτικά προσομοιώματα, κατακόρυφο δάσος, οπλισμένο σκυρόδεμα, πράσινα υλικά

SUMMARY

In the present deliverable report, the detailed development of the mathematical model for the digital twin model is presented, using the advanced Structural API (Application Programming Interface) of ReplicaXLite, which was developed with the assistance of the open-source finite element libraries OpenSeesPy and opstool, among else. The simulation was fully completed in the open-source programming environment Python 3 using the open-source Integrated Development Environment (IDE) Visual Studio Code. The developed simulation (ReplicaXLite Structural API) concerns both the first phase of testing as well as the second phase with the structural and green interventions, taking into account the different stages of interventions and additional masses. For the additional verification of the maximum base shear capacity at the expected maximum top displacement, a suitable three-dimensional finite element model was utilized in ANSYS Explicit Dynamics and the FRESCO database was developed. The above analytical investigations with three-dimensional finite elements, in combination with the experimental results, led to the optimization of the simulation with the ReplicaXLite Structural API. The models were tested both with Pushover Analysis as well as with Dynamic Time History Analysis using the ReplicaXLite Structural API. The results from the models were compared with the experimental results at the corresponding nodes, with the results from the measurement instruments of accelerations and displacements, common to both the first and second phases.

Keywords: digital twin model, analytical models, vertical forest, reinforced concrete, green materials

1 INTRODUCTION

The in depth literature review for the available mathematical models for proper material and elements definition for the project GREENERGY have been completed with the publication of Vanian et al. (Vanian, et al., 2025) and Deliverable D3.1 (Rousakis et al., 2024). For proper calibration and creation of similar RC Frame one-storey and one-bay as the GREENERGY project an extensive database of RC Frame systems that can be retrofitted with Fiber and Polymer Strengthening, namely FRESCO was developed (Vanian & Rousakis, 2025a). There in, three comprehensive examples for out of plane, in plane and full spatial model for Phase A for the GREENERGY were validated against experimental results. The advanced geometrical models generated from the FRESCO database can be used for proper simulation and calibration of the defined finite element models based on extensive sensitivity analysis of the various influential parameters (including materials and element non-linearities, geometry non-linearities, etc).

This deliverable (D3.2) presents the comprehensive development, calibration, and validation of digital twin model for both the as-built (Phase A) and renovated (Phase B) structural specimen tested within the GREENERGY experimental program. Building upon the literature review and modeling framework established in Deliverable D3.1 (Rousakis et al., 2024) and the experimental design documented in Deliverable D2.1 (Rousakis et al., 2024), this work implements advanced finite element modeling approaches using two complementary platforms: ANSYS Explicit Dynamics for preliminary validation and capacity assessment utilizing 3D finite elements and the open-source ReplicaX Lite Structural API (based on OpenSeesPy and opstool) for detailed dynamic time-history and pushover analysis utilizing advanced 1D finite elements. ReplicaX Lite Structural API enables step-by-step modifications of the model (addition or extraction of elements, modifications of mechanical properties by updating additional parameter, modification of mass). Additionally, with ReplicaX Lite Sensor API a practically real-time interoperability with physical model is enabled for the considered applications.

The numerical modeling strategy implemented in this work follows a hierarchical validation approach. Phase A modeling focuses on the as-built specimen representing typical Greek construction practice from the 1970s-1980s, characterized by limited seismic detailing and unreinforced masonry infills. The specimen was subjected to a progressive intensity shake table test protocol using the 1978 Thessaloniki earthquake record, with peak ground accelerations ranging from 0.1g to 1.1g, interspersed with white noise excitations for dynamic identification. Phase B modeling addresses the renovated configuration incorporating multiple innovative intervention technologies: (1) basalt fiber rope confinement of critical column regions, (2) steel-framed vertical living wall (VLW) systems with integrated planter pods, (3) polyurethane flexible joint (PUFJ) seismic isolation at infill-frame interfaces, (4) textile-reinforced mortar (TRM) jacketing of infill panels, and (5) integrated vegetation systems representing vertical forest implementation. The renovated specimen underwent an extended test sequence with peak accelerations reaching 1.4g, demonstrating the enhanced seismic capacity achieved through the combined intervention strategy.

Validation of the numerical models is performed through systematic comparison with experimental measurements at multiple sensor locations, including accelerometers at the foundation, beam-column joints, and infill centers, as well as displacement transducers monitoring lateral deformations at critical elevations. The comparison encompasses both global response metrics (base shear capacity, fundamental periods, drift ratios) and local response parameters (acceleration amplification, displacement profiles, damage progression). For Phase A, eleven test sequences are analyzed, while Phase B includes twenty-eight test

sequences covering a broader range of intensity levels to fully characterize the enhanced performance envelope of the renovated configuration.

The document is organized as follows: Chapter 2 presents the detailed 3D modeling methodology, including literature review of infill modeling approaches, current implementation details, mass distribution strategies, fiber-section definitions, boundary conditions, and ANSYS validation studies. Chapter 3 describes the pushover analysis implementation for the as-built structure, establishing baseline capacity. Chapter 4 presents comprehensive dynamic time-history analysis results for Phase A, comparing numerical predictions with experimental data for all eleven test sequences. Chapter 5 extends the pushover analysis to the renovated structure, quantifying capacity enhancement. Chapter 6 presents dynamic time-history results for Phase B across twenty-eight test sequences. Chapter 7 summarizes key findings and recommendations for future research and practical implementation.

2 3D STRUCTURE MODELING

The current implementation of the 3D numerical modeling follows straightforward practical engineering steps so that in the future, similar models will be able to verify suitable complex structures, given the generalization of the results from the current experiment. Having this in mind, a general-purpose model that can be designed in common finite element packages that support fiber sections capabilities (or advanced non-linear materials and elements) was proposed. This approach ensures accessibility and reproducibility for engineering practitioners and researchers working with advanced structural analysis.

The methodology incorporates calibrated material constitutive relationships derived from extensive experimental testing, allowing for accurate prediction of both elastic and inelastic structural behavior. By utilizing discrete fiber elements to represent cross-sectional properties, the model can effectively capture local damage phenomena and progressive failure mechanisms that are often overlooked in simplified analytical approaches. Furthermore, the implementation accounts for geometric nonlinearities and second-order effects, which are critical for structures subjected to significant lateral loading or those with slender components exposed to seismic excitations.

Validation studies comparing numerical predictions with experimental results are crucial in order to demonstrate the model's robustness across unidirectional seismic test protocols utilizing a range of acceleration intensity measures for Phase A (0.1g, 0.2g, 0.5g, 0.8g, 1.1g) and for Phase B (0.07g, 0.1g, 0.14g, 0.2g, 0.34g, 0.5g, 0.55g, 1.1g, 1.3g, 1.4g). These progressive intensity levels allow for comprehensive assessment of structural behavior from elastic response through various damage states to inelastic response. The proposed framework also offers significant computational efficiency compared to more complex micro-modeling techniques, providing an optimal balance between accuracy and practical application in engineering research and application. Additionally, the model's parametric nature facilitates sensitivity analyses and optimization studies, enabling engineers to rapidly evaluate multiple design alternatives and identify critical parameters affecting structural performance under various seismic demand scenarios, particularly for structures exposed to the intensity range tested in the experimental program.

In chapter 2.6 the verification examples from the FRESCO database (Vanian & Rousakis, 2025a) for GREENERGY are presented.

2.1 INFILL MACRO MODELING APPROACHES

In the literature, there are many studies that provide a specific design approach for infill panels that are used in reinforced concrete frames. Among others the most relevant numerical studies with their core theoretical background are presented and then summarized (see Table 1 and Figure 1). Afterwards, a detailed explanation of the current implementation approach of infills are presented and a flow diagram for the parameter identification is provided for convenience (see Figure 3).

2.1.1 Literature review of the relevant infill models

In the current implementation of the macro-modeling approach adopted for infill panels in this research, numerous studies have been considered that address in-plane, out-of-plane, and the interaction between these response mechanisms. Several of these studies specifically incorporate mass distribution considerations for seismic excitation analysis. There are recent literature review papers on this issue, such as the one by (Bouarroudj & Boudaoud, 2022; Rostamkalae et al., 2023) that are reported here. The following description progresses systematically from the simplest modeling approaches to more complex methodologies that comprehensively account for multiple aspects of structural response behavior as described in (Bouarroudj & Boudaoud, 2022).

Holmes (Holmes, 1961) introduced the straightforward "one-third rule," according to which the strut width is equal to one-third of the infill diagonal length, which marked the beginning of the development of equivalent diagonal strut approaches for modeling masonry infills. This

idea was greatly expanded upon by Smith (Smith, 1962) who introduced the critical parameter of "relative stiffness" (λh) between the infill and surrounding frame, which takes into account the geometrical and elastic properties of both elements. This parameter became essential to later modeling techniques. By creating an empirical equation that connected strut width to the relative stiffness parameter ($w = 0.175 \cdot d \cdot (\lambda h)^{-0.4}$), Mainstone (Mainstone, 1974) improved the diagonal strut methodology even further. This equation was later incorporated into seismic rehabilitation guidelines like FEMA 356 (FEMA 356, 2000). These three studies laid the groundwork for later researchers to create increasingly complex models, such as multi-strut approaches and models that take into account both in-plane and out-of-plane behavior.

Chrysostomou et al. (Chrysostomou et al., 2002) suggested a six-strut model (Figure 1B), three struts in each direction. The model contains one diagonal strut and two off-diagonal struts positioned at the critical points of frame members where plastic hinges are likely to form. At any instance, only three of the six struts are active, which switch to the opposite direction when they reach zero forces. The model accounts for both strength and stiffness degradation through a smooth continuous strength envelope and hysteretic loop equation.

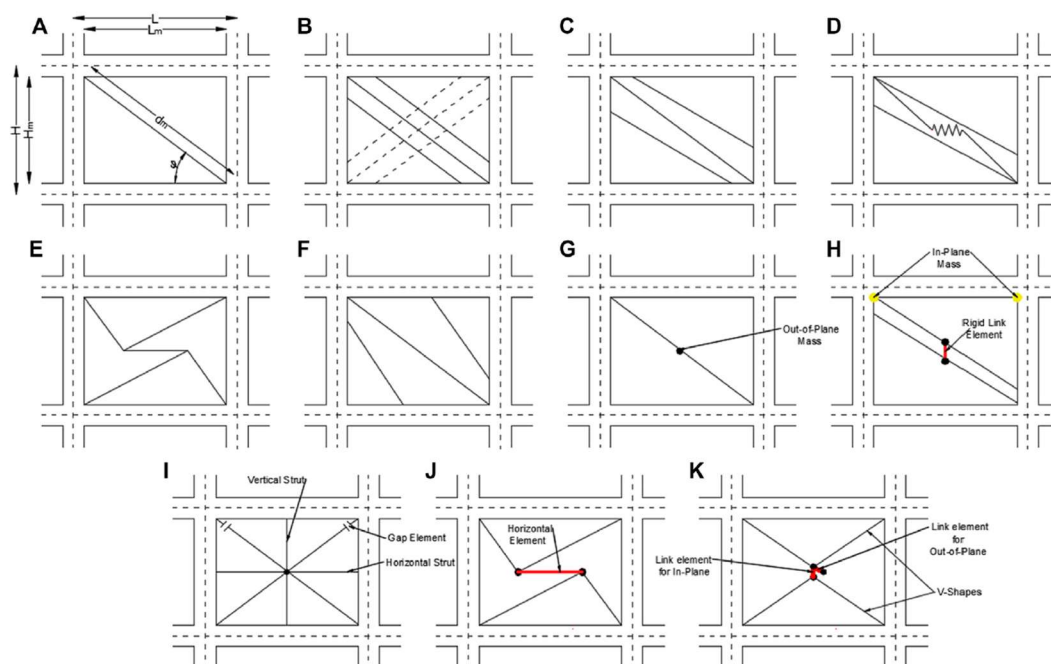


Figure 1 Macro models: (A) one diagonal strut model (B) multi-strut model of (Chrysostomou et al., 2002) (C) (El-Dakhakhni et al., 2003) (D) (Crisafulli & Carr, 2007) (E) (Rodrigues et al., 2010) (F) (Yekrangnia & Mohammadi, 2017) (G) (Kadysiewski & Mosalam, 2009) (H) (Donà et al., 2017) (I) (Di Trapani et al., 2018) (J) (Furtado et al., 2015) (K) (Gesualdi et al., 2020) [adapted from (Bouarroudj & Boudaoud, 2022)]

El-Dakhakhni et al. (El-Dakhakhni et al., 2003) proposed a multi-strut model (Figure 1C) to incorporate the effects of masonry infills on the stiffness and strength of infilled steel frames. According to the study, the complexity and accuracy of macro-models are dependent on the number of struts. As an example, a three-strut model is more complicated and accurate than the single and two-strut models. This approach allows for more accurate simulation of the frame-infill interactions and accounts for the localized effects at beam-column junctions where significant stresses develop during lateral loading. Crisafulli and Carr (Crisafulli & Carr, 2007) represented masonry infills with two diagonal struts connected by a shear spring, as shown in Figure 1D. The objective of the shear spring is to represent the shear behavior of the masonry wall. This model accounts for the sliding shear mechanism that frequently occurs along mortar bed joints during lateral loading. By incorporating this mechanism, the model better captures one of the principal failure modes observed in experimental testing. The dual-strut configuration with the connecting spring provides a more comprehensive representation of

both diagonal compression and shear mechanisms. The model by Rodrigues et al. (Rodrigues et al., 2010) is formed by four struts related to each other with a horizontal central element (Figure 1E). This configuration creates a system that distributes lateral forces throughout the infill panel more effectively than single-strut models. The central connecting element enables load transfer between the diagonal components, allowing for a more realistic simulation of the actual force path within the masonry infill. This approach provides a balance between computational efficiency and accuracy in representing the global behavior of infilled frames under lateral loads. Based on a numerical study using ABAQUS, Yekrangnia and Mohammadi (Yekrangnia & Mohammadi, 2017) proposed a multi-strut model. At a lower drift level, the authors observed the formation of a single diagonal strut. At high drifts, the single strut developed into two diagonal struts. Based on these observations, they proposed a three-strut model. The model is composed of one diagonal and two off-diagonal struts, as shown in Figure 1F. Equation (1) was proposed to calculate the width (w_p) of the off-diagonal struts.

$$w_p = 0.001w_M(6\theta + 7.5\alpha_p) \quad (1)$$

$$l_{ceff-p} = 0.006h(\theta + \alpha_p - 10\lambda h) \text{ where } \alpha_p = \alpha - \lambda_h h \text{ and } \alpha = \tan^{-1}\left(\frac{1}{\mu}\right) \quad (2)$$

This equation is related to the model width w_M proposed by Mainstone R. J. (Mainstone, 1971, 1974) where θ and α_p are the inclination of the diagonal and off-diagonal struts (in degrees), respectively. For the diagonal strut, the width is considered to be one-half the off-diagonal width. Equation (2) defines the positions (l_{ceff-p}) of the off-diagonal struts. Kadysiewski and Mosalam (Kadysiewski & Mosalam, 2009) developed a practical model to include the effect of the in-plane and the out-of-plane behaviors of the masonry infill. The proposed model is based on representing the masonry infill with a single diagonal strut, which is sufficient to represent both behaviors of the masonry infill, works in tension and compression, and has a lumped mass at the mid of the diagonal length that works in the out-of-plane direction. Figure 1G illustrates the model proposed by Kadysiewski and Mosalam 2009. This approach provides computational efficiency while still accounting for the dual-directional response of infill panels. Donà et al. (Donà et al., 2017) proposed a two-strut model to combine both behaviors (Figure 1H). Their model is developed based on the model proposed by (Mosalam & Günay, 2015). This model contains two diagonal struts modeled as the same way as (Crisafulli & Carr, 2007)'s model. Donà et al. 2017 assigned two types of masses. The first type works in the in-plane direction, located at each beam-column joint. The second type works in the out-of-plane direction located at the mid-length of each strut and connected with a rigid link element. This dual mass system allows for more accurate simulation of seismic inertial forces in both directions. Di Trapani et al. (Di Trapani et al., 2018) developed a macro-model that is applicable in static and dynamic analyses. The proposed model contains four struts, a vertical and a horizontal strut, and two diagonal struts, one in each direction. Each strut represents two beam-column elements with fiber cross sections. The authors report that the model can capture the arching action of the out-of-plane deformation and the interaction of the in-plane and out-of-plane behaviors. Figure 1I illustrates the model proposed by Di Trapani et al. 2018. The implementation of fiber sections enables detailed simulation of material nonlinearity and stress distributions across the section depth. Furtado et al. (Furtado et al., 2015) developed the multi-strut model proposed by (Rodrigues et al., 2010) to account for the in-plane and out-of-plane interaction. Later, the out-of-plane masses are assigned to the two extremity nodes of the horizontal element, as illustrated in Figure 1J, by (Mazza & Donnici, 2021). This implementation makes the model more accessible for practicing engineers conducting seismic analyses of building structures. Gesualdi et al. (Gesualdi et al., 2020) studied the seismic performance of residential RC buildings by considering the two behaviors. The masonry infill is modeled with four diagonal struts forming two V-shapes. The V-shapes are connected with nonlinear zero-length link elements to reproduce the in-plane degradation due to the cyclic load. The same link element type is used to model the out-of-plane degradation. A lumped mass represents the out-of-plane mass that is assigned to the node that connects V-shapes. Figure 1K illustrates the model with V-shapes. This configuration effectively captures both the in-plane

and out-of-plane response while maintaining computational efficiency. For additional implementation models readers can refer to (Rostamkalaei et al., 2023).

Table 1 Different macro-models for infills and their design approaches

Note1: Studies adapted from literature review in the (Bouarroudj & Boudaoud, 2022)

Note2: “-” indicate additional steps may be required

Core Study/ Document	Stiffness/ Strength		Mass		Design approach
	IP	OOP	IP	OOP	
(Chrysostomou et al., 2002)	✓	-	-	-	Six compression-only struts with hysteretic model for strength/stiffness degradation. Captures frame-infill interaction and local behaviors.
(El-Dakhkhni et al., 2003)	✓	-	-	-	Three compression-only struts (one diagonal, two off-diagonal) representing orthotropic masonry with trilinear stress-strain behavior. Models frame-infill interaction and corner crushing failure.
(Crisafulli & Carr, 2007)	✓	-	-	-	Four-node panel element with two parallel compressive struts and a shear spring in each direction. Separates axial and shear behavior, models hysteretic response with strength/stiffness degradation, and captures different shear failure modes.
(Rodrigues et al., 2010)	✓	-	-	-	Enhanced bi-diagonal strut macro-model with direction interaction. Central nonlinear strut element with multi-linear envelope and hysteretic rules for stiffness/strength degradation and pinching.
(Yekrangnia & Mohammadi, 2017)	✓	-	-	-	New diagonal strut model with modified angle and effective length formulations. Calibrated through FE analysis to better capture frame internal forces. Considers infill-frame interaction with friction coefficient between bricks.
(Kadysiewski & Mosalam, 2009)	✓	✓	✓	✓	Single strut macro-model that can account for the in-plane and out-of-plane interaction.
(Donà et al., 2017)	✓	✓	✓	✓	Two-strut macro-model with hysteretic behavior to simulate IP-OOP interaction. Captures strength/stiffness degradation with fiber sections symmetrically placed out-of-plane. Calibrated from experimental tests on thick and thin infill panels.
(Di Trapani et al., 2018)	✓	✓	-	-	Four-strut model (two diagonal, one horizontal, one vertical) using fiber-section beam-column elements. Captures arching action for OOP response and IP-OOP interaction. Diagonal struts provide IP resistance while all struts contribute to OOP resistance.
(Furtado et al., 2015)	✓	✓	-	-	Improved bi-diagonal strut model with four rigid support struts and one central nonlinear element. Central element uses Pinching4 material in OpenSees to model hysteretic behavior with strength/stiffness degradation. Parameters calibrated with experimental data.
(Gesualdi et al., 2020)	✓	✓	✓	✓	V-shaped bi-diagonal strut macro-element with two sets of nonlinear zero-length link elements. Models IP/OOP interaction through semi-empirical relationships. Includes both strength/stiffness degradation and a routine that removes infills when either IP or OOP collapse occurs. OOP mass (80% of infill total mass) lumped at midpoint.

2.2 CURRENT INFILL MODELING

In the current research the modeling approach for the unreinforced infills follows the one proposed by (Di Trapani et al., 2018) and was modified by (Pradhan & Cavaleri, 2020). The main changes that the later research implemented were to replace the pin-connected end conditions with fixed-end connections (this modification was implemented to limit excessive mid-span deflections and enhance the arching mechanism under out-of-plane loading conditions) for all struts and to adopt unified material properties for all infill elements (adopting a single effective compressive strength value for defining the compressive behavior of all struts, thereby reducing the complexity of parameter calibration). See Figure 2 for more details. The modified model utilizes surrogate thickness values for all struts (diagonal, horizontal, and vertical). This ensures consistent cross-sectional treatment across all equivalent strut elements. While the original model relied on empirical assignment of mechanical characteristics (deformation at peak strength ϵ_o , ultimate strength f_{mu} , and ultimate strain ϵ_{mu}) without systematic procedures, the modified model introduces a standardized methodology for deriving these parameters through correlation equations based on the actual mechanical properties of the masonry infill.

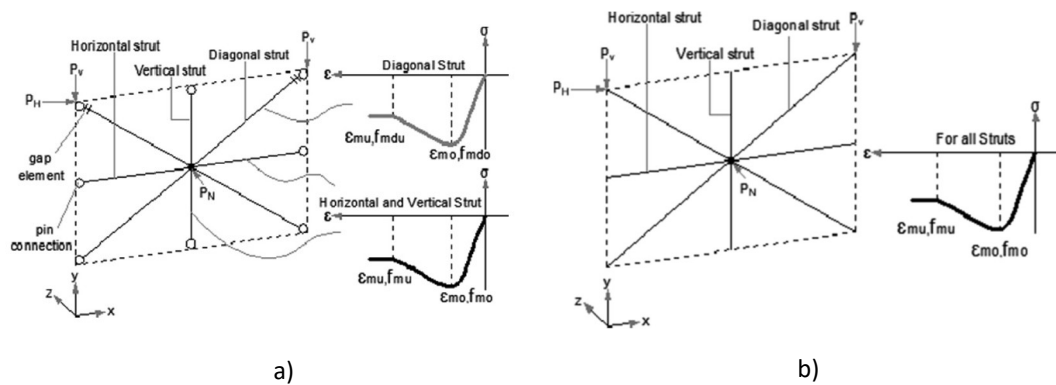


Figure 2 Proposed model from a) (Di Trapani et al., 2018) and b) (Pradhan & Cavaleri, 2020) adapted from (Pradhan & Cavaleri, 2020)

The mass application in the proposed modified four-strut macro model, centers on four mid-span nodes located at the geometric center of the infill panel, positioned at the intersection of the diagonal, horizontal, and vertical struts. The total mass of the infill wall is concentrated at these four central nodes using a lumped mass approach, which simplifies dynamic analysis while maintaining sufficient accuracy for practical engineering applications. The critical aspect of this mass system is the constraint mechanism governing these mass-bearing nodes. Each of the four mid-span nodes can exhibit different displacements in the plane of the infill (allowing for complex stress distributions during in-plane loading), but they are rigidly connected in the out-of-plane direction, ensuring the entire infill mass moves as a cohesive unit when subjected to lateral loads perpendicular to the wall plane. This constraint system enables the model to capture the arching mechanism that develops in masonry infills under OOP loading, where mass distribution and inertial effects are crucial. The practical application involves applying OOP loads directly to these central mass nodes, as described in the validation studies where "the OOP load was applied at the center of the struts representing the infill center." This loading approach ensures that applied forces are transmitted through the constraint system to all four struts simultaneously, activating the bending response in the fiber-section beam-column elements. While the paper doesn't provide explicit mass distribution equations, the approach assumes the total infill mass is equally distributed among the four central nodes, consistent with the macro-modeling philosophy that prioritizes computational efficiency for large-scale structural analysis.

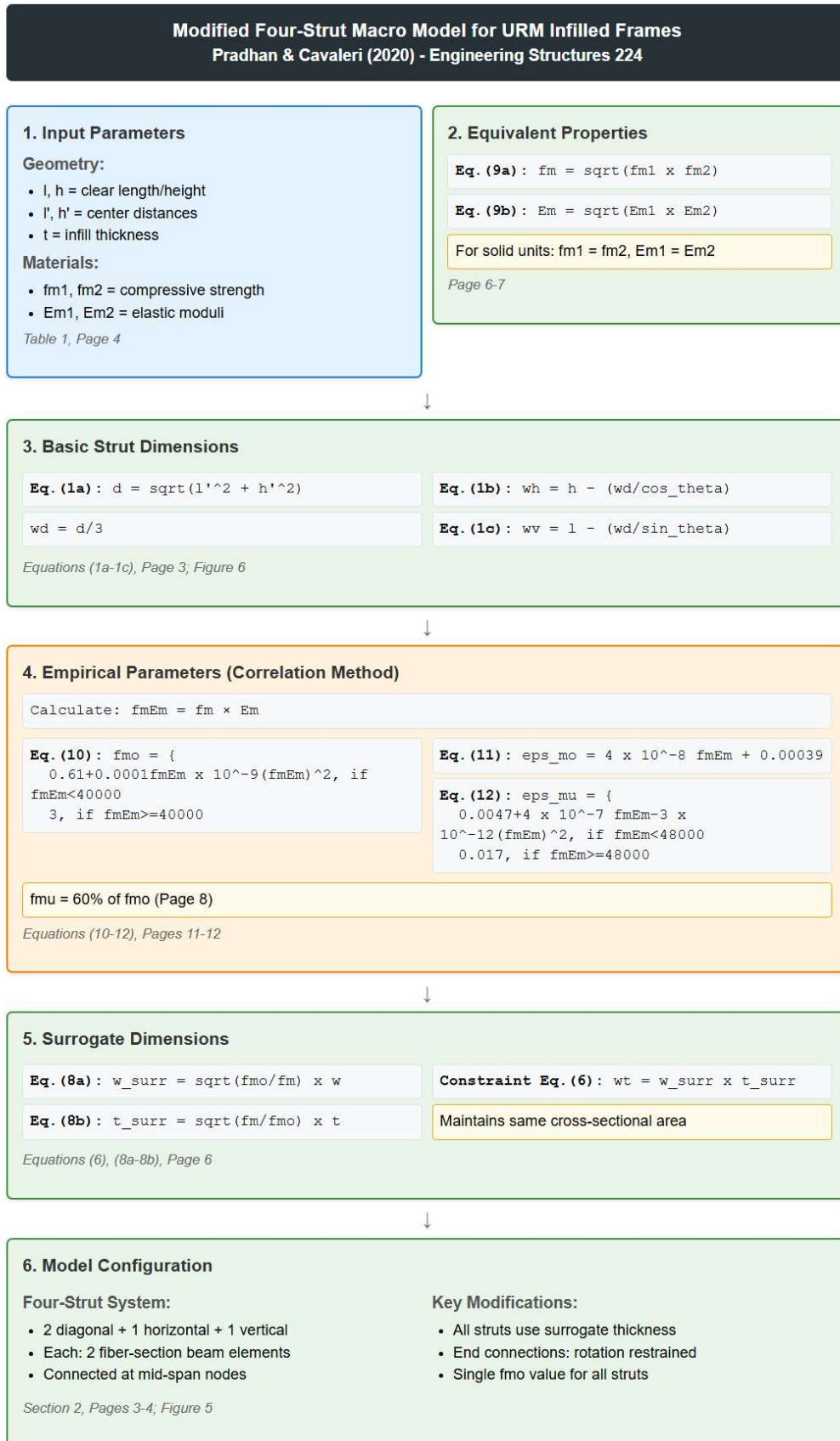


Figure 3 Summary workflow for infill parameters identification based on (Pradhan & Cavaleri, 2020)

2.3 MASS DISTRIBUTION

The total mass was distributed in the model using a lumped approach, which means the masses are concentrated in certain nodes of the structure that are considered critical mass regions based on the current distribution approach. Specifically, these masses were concentrated at the top of the column free ends, in the cantilever edges, and at the beam-column joints intersection points. Regarding the infill, the mass was concentrated in the intersection point of the four equivalent struts. In the in-plane direction, the four struts were designed to move independently; however, for the out-of-plane direction, they were constrained to act as a single mass. Furthermore, the distribution of the mass takes into account the special beam-column parts, while excluding the missing portion of the cantilever. Generally, the overall mass distribution follows a symmetrical approach throughout the structure. This means that half of each column's mass is assigned to its upper node and the remaining half to its lower node. Similarly, this principle applies to the beams as well. Following this proportional distribution method, for each beam element, the mass is evenly divided with half allocated at the beginning and half at the end. The total mass is depicted in Table 2 and node positions in Figure 4.

Table 2 Mass distribution table for as built model

Group	Mass (kg)	Mass Portion (%)	Nodes
Top Column Corners	41.29	1.0	1-4
Beam-Column Joints	2075.44	48.1	5-8
Cantilever Edges	798.39	18.5	9-16
Bottom Beam-Column Joints	979.00	22.7	17-20
Base Beam Edges	223.59	5.2	21-28
Full Infills	157.98	3.7	41-48
Partial Infills	38.22	0.9	49-50, 53-54
Total	4313.91	100	1-50, 53-54

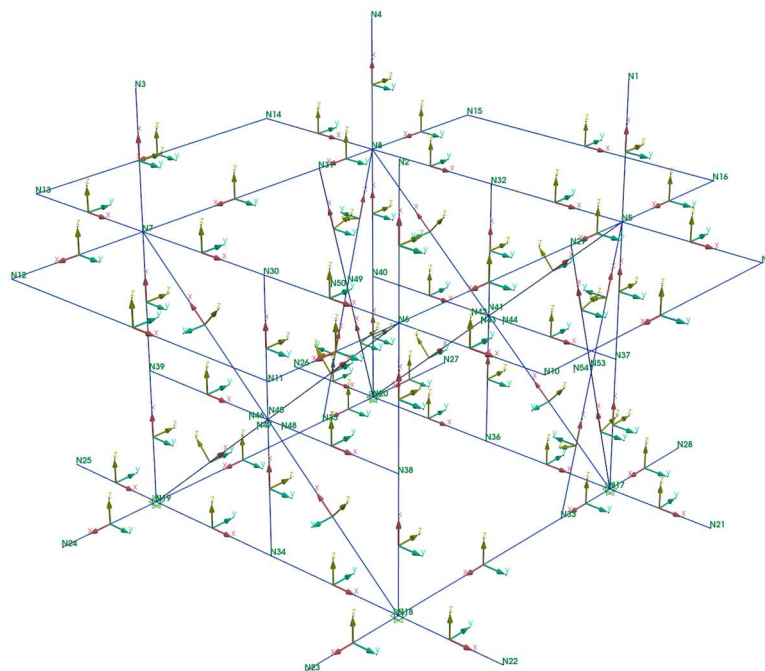


Figure 4 Node positions for numerical model of as built structure

2.4 STRUCTURAL COMPONENT CROSS-SECTION DEFINITION

All structural components were modeled using fiber section and ForceColumn beam elements available in OpenSees (McKenna, 2011). The exact geometry and rebar position were provided in the models alongside with material properties identified during experimental setups. Columns were design with $0.13 \times 0.13 \text{ m}^2$ cross-section and $4\Phi 8$ longitudinal rebars with $f_y=564 \text{ MPa}$ and $E_s=195.2 \text{ GPa}$ using Steel02 material model for Concrete Concrete02 with compression strength for core 25.8 MPa both are available in OpenSees material library (see Figure 5a). The hidden beams that connect the beam-column joints were modeled with $0.343 \times 0.2 \text{ m}^2$ cross-section with $8\Phi 10$ longitudinal rebars (for hidden beam) and $4\Phi 10$ for the Slab contribution. The concrete compression strength for the core was 32.63 MPa . The cross-section is depicted in Figure 5b. In Figure 5c is provided the base beam cross-section of $0.20 \times 0.25 \text{ m}^2$ with $8\Phi 14$ longitudinal rebars. The concrete compression strength was defined in core as 37.76 MPa . For the cantilever the cross-section was used as depicted in Figure 5d with the same material properties as in the hidden beams. For all concrete cores the compressive strength was 1.05 times the strength in the cover section. The infills were designed with material Concrete02 with compressive strength 1.15 MPa and geometrical properties that were computed from flowchart of Figure 3.

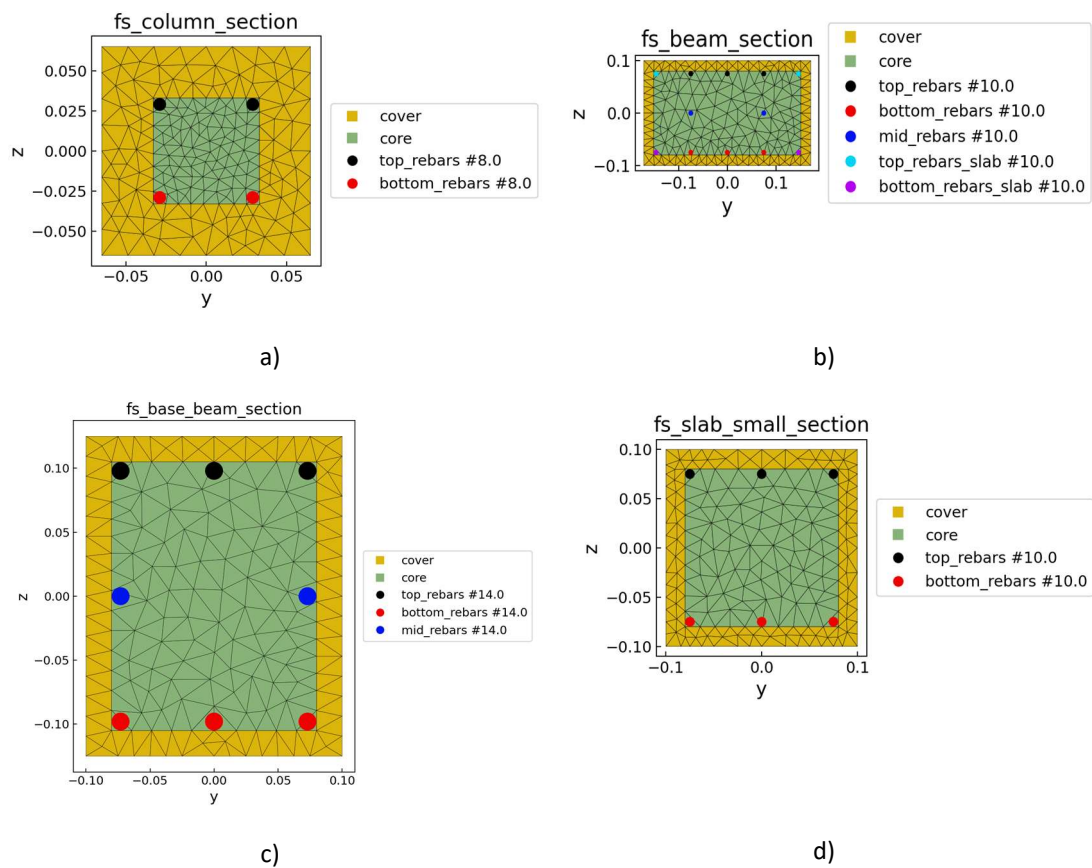


Figure 5 Fiber-Section Definition for as Built Specimen for a) columns b) hidden beams c) base beams and d) cantilever beams

2.5 CONSTRAINTS AND GRAVITY LOADS

The model was constrained in all global translational direction X,Y,Z at the bottom of the columns (nodes 17,18,19,20) as depicted in Figure 6 with green rectangle notations. The slab level was constraint with diaphragm command in the XY global surface with master node 5. The nodes of the infills centers were constrained to move as one in the out of plane direction using equal degree of freedom command. All information is depicted in Figure 6.

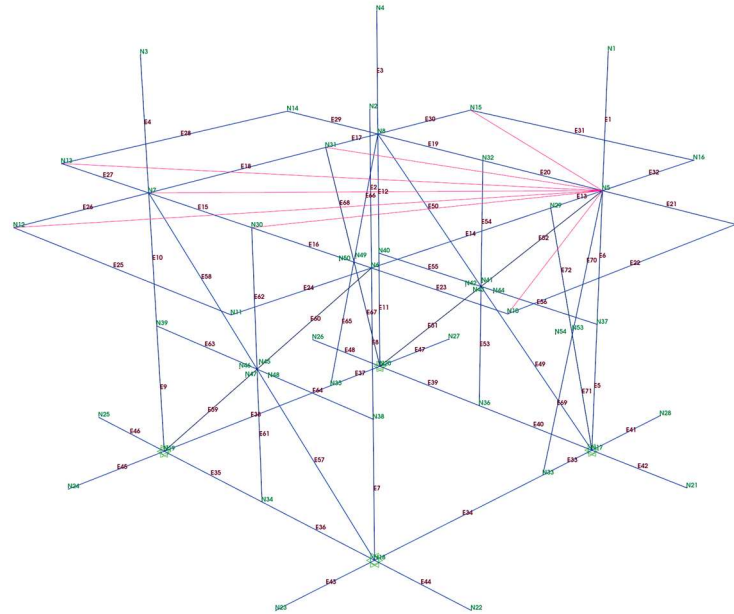


Figure 6 Constraints for as built specimen

Gravity loads proportional to the mass of each node were applied in the -Z global direction by multiplying the mass with the gravitational acceleration of 9.81m/s^2 as depicted in Figure 7.

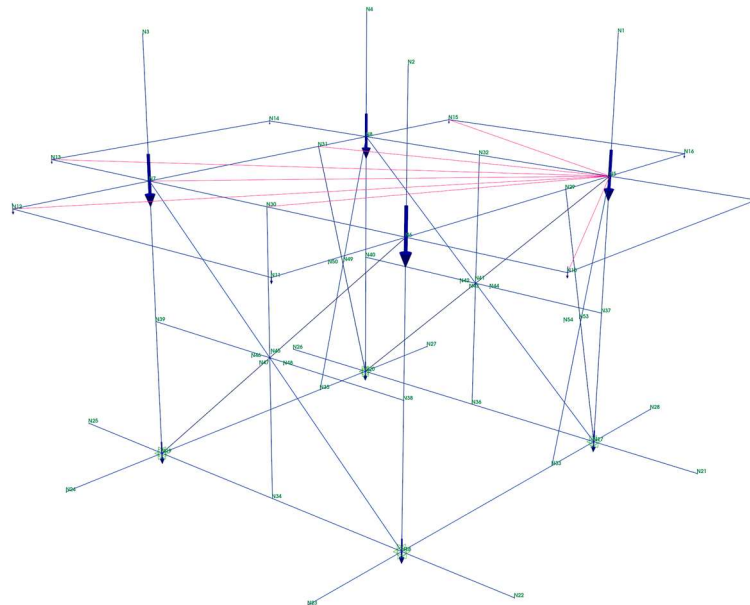


Figure 7 Gravity Loads applied to as built specimen

2.6 ANSYS EXPLICIT DYNAMIC PUSHOVER SIMULATION PHASE A

The spatial model from the FRESCO Database (Vanian & Rousakis, 2025a) examples, examines the single-story structural specimen developed within the GREENERGY project Phase A, see Deliverables 2.1 (Rousakis, et al., 2024), which was specifically constructed to represent Greek building practices from the pre-Eurocode era. The specimen enabled comprehensive evaluation of seismic behavior and retrofit effectiveness for vertical forest systems (Theodoridou et al., 2025; Vanian, et al., 2025; Vanian, Rousakis, et al., 2025) through multiple shake table experiments conducted at the Reinforced Concrete and Seismic Design laboratory of Democritus University of Thrace (DUTH).

The structural configuration included four square columns measuring 130 mm × 130 mm, which were supported by robust foundation beams firmly attached to the shake table platform. These columns were connected at the top level through concealed beams and an overhanging slab. Column reinforcement comprised four corner bars of 8 mm diameter with transverse ties of 5.5 mm diameter spaced at 60 mm centers (refer to Figure 8).

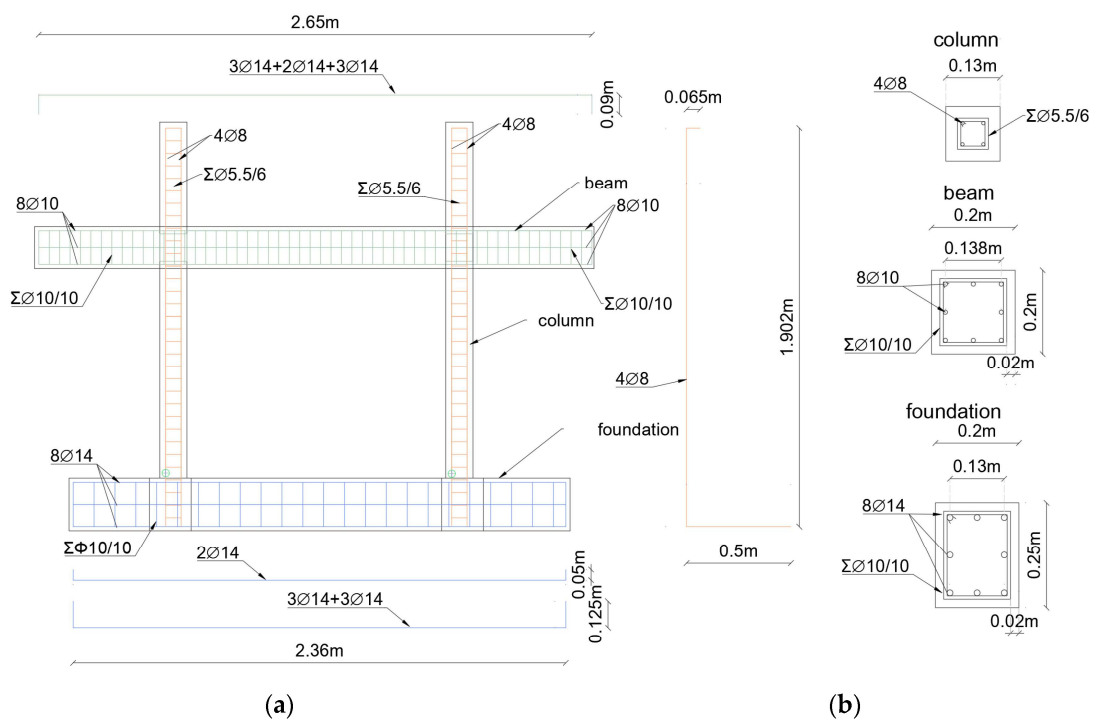


Figure 8 GREENERGY-1 specimen model: (a) geometry with reinforcement and (b) cross sections (adapted from (Vanian & Rousakis, 2025a))

Figure 9a and Figure 9b illustrates the geometry as originally produced by the database algorithm and after subsequent manual refinement, respectively. The database-generated geometry required proper spatial orientation around the structure's central axis, which initially resulted in element overlap. Overlapping components were merged, and the finalized spatial model was established. To eliminate excess material and produce the final configuration, square sections at beam-column intersections were removed for both linear and solid element types. The model shown in Figure 9b was subjected to boundary conditions with fixed supports at the base and analyzed using a pushover procedure (with controlled displacement at slab level at X global direction) to establish the peak capacity corresponding to a 1% drift ratio associated with the Serviceability Limit State (SLS).

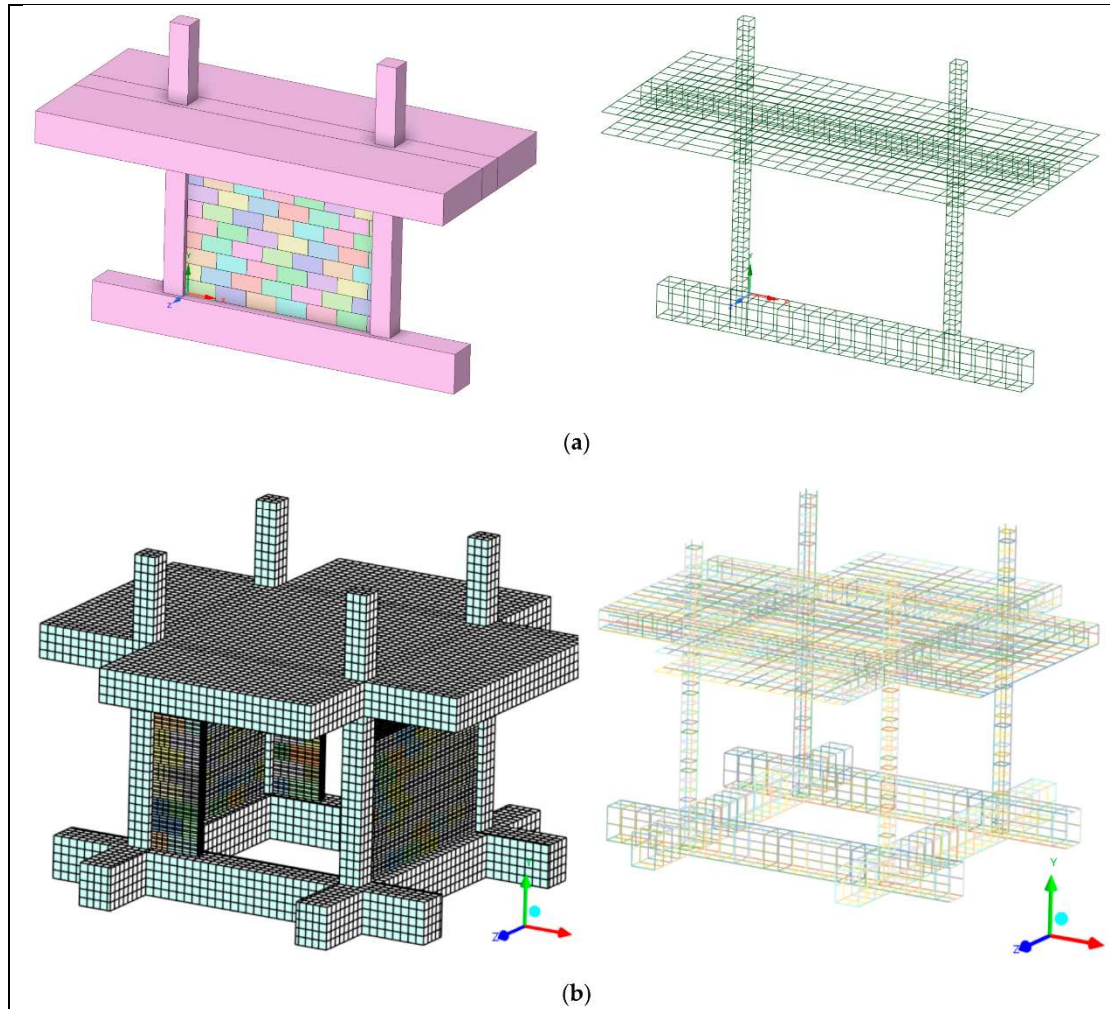


Figure 9 GREENERGY-1 model generated by (a) database code and (b) manually edited inside FEM analysis. (adapted from (Vanián & Rousakis, 2025a))

The as-built specimen underwent shake table testing without any strengthening measures, subjected to 12 consecutive loading sequences alternating between the 1978 Thessaloniki earthquake record and white noise excitations. This initial testing phase (as-built, phase A) concluded when the maximum induced peak ground acceleration reached 1.1 g. At this final excitation level, the specimen experienced deformations corresponding to a 1% drift ratio while resisting a total lateral force of approximately 50 kN—a value that demonstrated good agreement with numerical predictions.

Regarding damage progression, Figure 10 a,b presents comparative results from two distinct perspectives. The lateral perspective (Figure 10a) reveals that experimental damage, marked by red lines, concentrated predominantly at the structure's lower regions and along frame-infill boundaries. The accompanying numerical simulation displays stress concentrations (depicted in green and yellow) that correspond closely with these experimentally documented damage zones. The stress patterns reveal elevated strain accumulation at the base-wall connection and within specific joint areas.

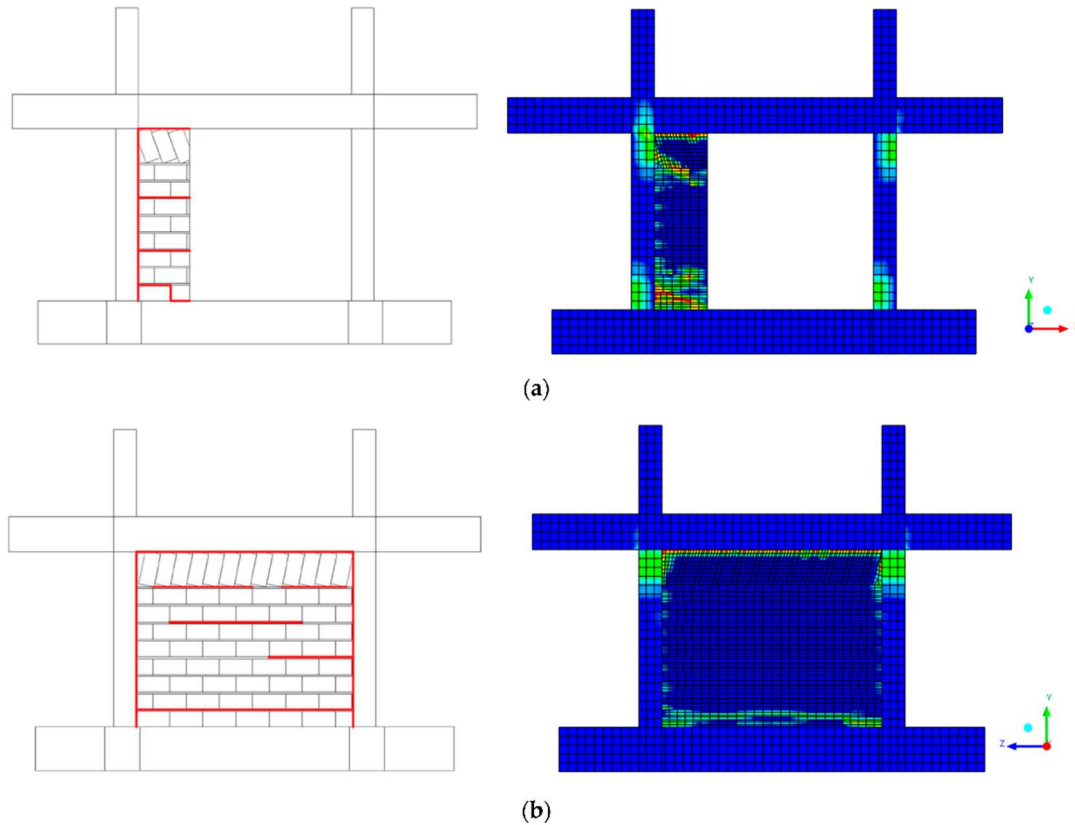


Figure 10 GREENERGY-1 result for explicit dynamic analysis of the failure mechanism for EQ 1.1 g: (a) side view and (b) front view. (adapted from (Vanian & Rousakis, 2025a))

The frontal perspective (Figure 10b) offers additional insight into damage evolution. The experimental observations show more widespread cracking throughout the wall surface, with horizontal crack development represented by red markings. The numerical simulation effectively captures this response, demonstrating stress concentrations that spatially correspond with the experimental crack distribution. The color spectrum ranging from blue (minimal stress) to green/yellow (elevated stress) effectively identifies regions of damage inception and advancement. Notably, both representations highlight significant debonding phenomena occurring at the frame-infill connections.

Additional sensitivity analysis for out-of-plane and potential retrofitting were performed in the Example 1 and Example 2 in the FRESCO database (Vanian & Rousakis, 2025a). The results are presented in the Figure 11 and Figure 12. For these examples, Method V2 was used for the modeling of reinforcement, taking reinforcement interactions into proper account as described in (Vanian et al., 2024). Example 1 examined the S_CON specimen from Koutas and Bournas (Koutas & Bournas, 2019), featuring a single-wythe unreinforced infill under out-of-plane loading. The response curve closely matched experimental data in terms of initial stiffness, peak loading, and post-peak degradation, while the failure pattern successfully captured the typical arching mechanism. Example 2 analyzed specimens SIF-I-A (unstrengthened) and SIF(DTRM)-I-B (TRM-strengthened) from Akhoundi et al (Akhoundi et al., 2023) under in-plane loading. The numerical models showed good agreement with experimental P-d curves, with the strengthened specimen demonstrating enhanced stiffness and strength. The crack patterns, including diagonal cracking through masonry and damage at column regions, were successfully reproduced, validating the modeling approach for both loading conditions and retrofitting scenarios.

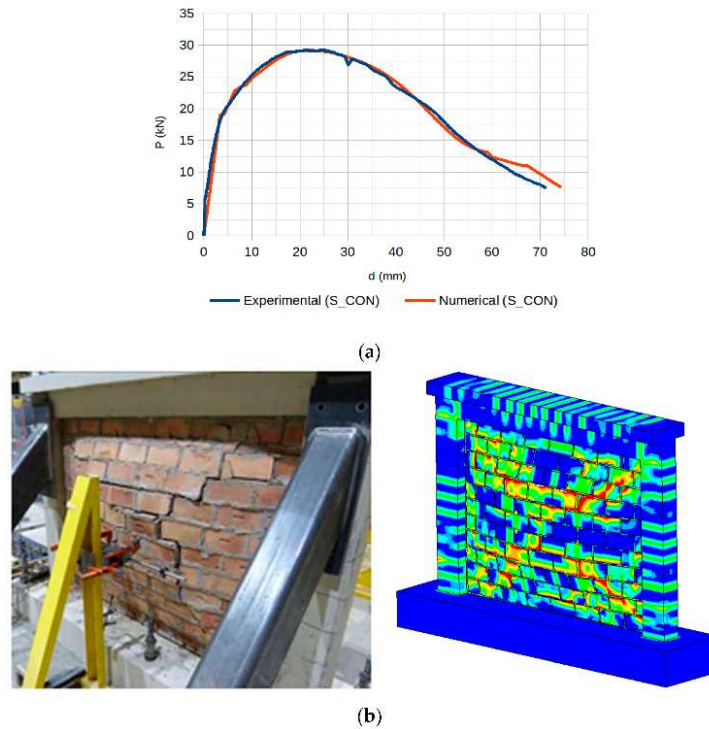


Figure 11 FRESKO database Example 1 results for out-of-plane specimen a) P-d curve b) damage visualization (adapted from (Vanian & Rousakis, 2025a))

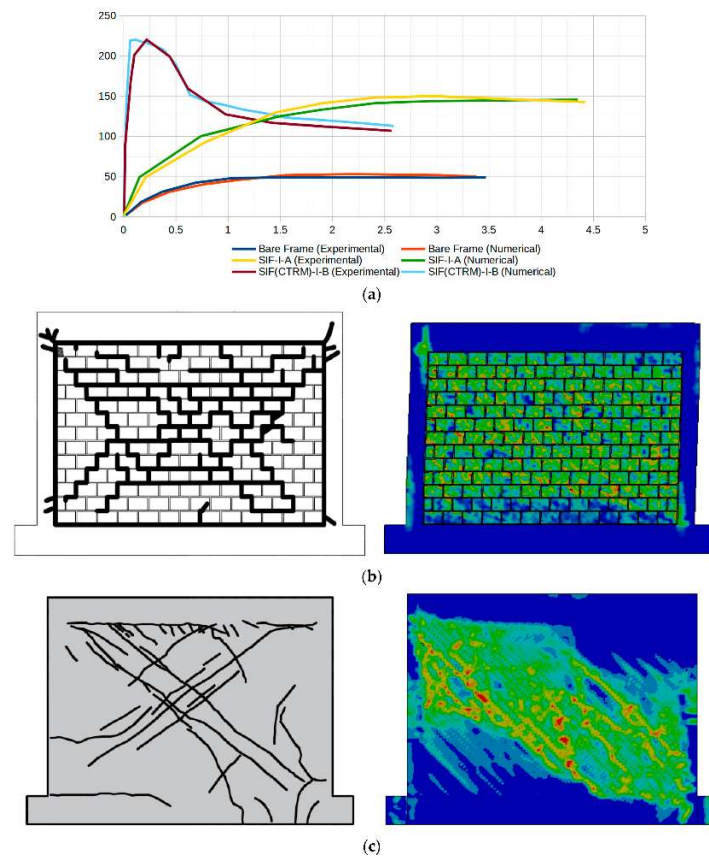


Figure 12 FRESKO database Example 2 results for in-of-plane specimen and strengthening a) P-d curve b) damage visualization (adapted from (Vanian & Rousakis, 2025a))

With three comprehensive examples for out-of-plane, in-plane, and the creation of a full spatial model for Phase A of the GREENERGY project, it was validated that the advanced geometrical models generated from the FRESCO database can be used for proper simulation and calibration of the defined finite element models based on extensive sensitivity analysis of the various influential parameters. The RHT (Riedel-Hiermaier-Thoma) concrete material model employed in ANSYS Explicit Dynamics required careful parameter calibration to capture concrete behavior under dynamic loading. The RHT model incorporates multiple pressure-dependent failure surfaces with parameters highly sensitive to mesh size, strain rate effects, and compressive strength. All RHT parameters scale proportionally with compressive strength, necessitating systematic calibration for the experimental concrete grade. Dynamic strength shows significant sensitivity to strain rate exponents, potentially varying $\pm 5\text{-}10\%$, directly affecting prediction accuracy under seismic loading. The bilinear isotropic hardening model for steel reinforcement requires precise determination of yield strength and tangent modules. The ratio of plastic modulus to Young's modulus significantly influences plasticity behavior and cyclic response. The embedded reinforcement approach enables efficient discretization while maintaining accurate load transfer, though requiring verification of steel-concrete bond behavior under dynamic conditions. This comprehensive sensitivity analysis of material and geometry non-linearities was essential to predict (in agreement with) the future experimental results—50 kN lateral capacity and 1% drift ratio at 1.1g excitation (before the execution of tests—pre testing).

3 IMPLEMENTATION OF THE PUSHOVER ON THE AS-BUILT STRUCTURE

The pushover analysis was implemented as a static nonlinear analysis procedure to evaluate the seismic performance of the as-built structure under lateral loading conditions. This method involves applying incremental lateral loads to the structure while monitoring its response until desired displacement is reached. The `run_pushover_analysis` command from the ReplicaXLite Structural API was used. The key implementation steps are:

- **Load Pattern Creation:** A new load pattern was created with a linear time series to simulate progressive lateral loading
- **Control Node Selection:** Node 5 was selected as the control node for the pushover analysis, with degree of freedom 1 (X-direction) being monitored
- **Loading Protocol:** The analysis employed a target protocol approach with a maximum displacement step of 0.013 meters divided into 100 increments
- **Analysis Parameters:** The standard OpenSees analysis parameters were used with default convergence criteria

The lateral loads were applied to nodes 5 and 8 as depicted in Figure 13. The result of the Pushover analysis is depicted in Figure 14.

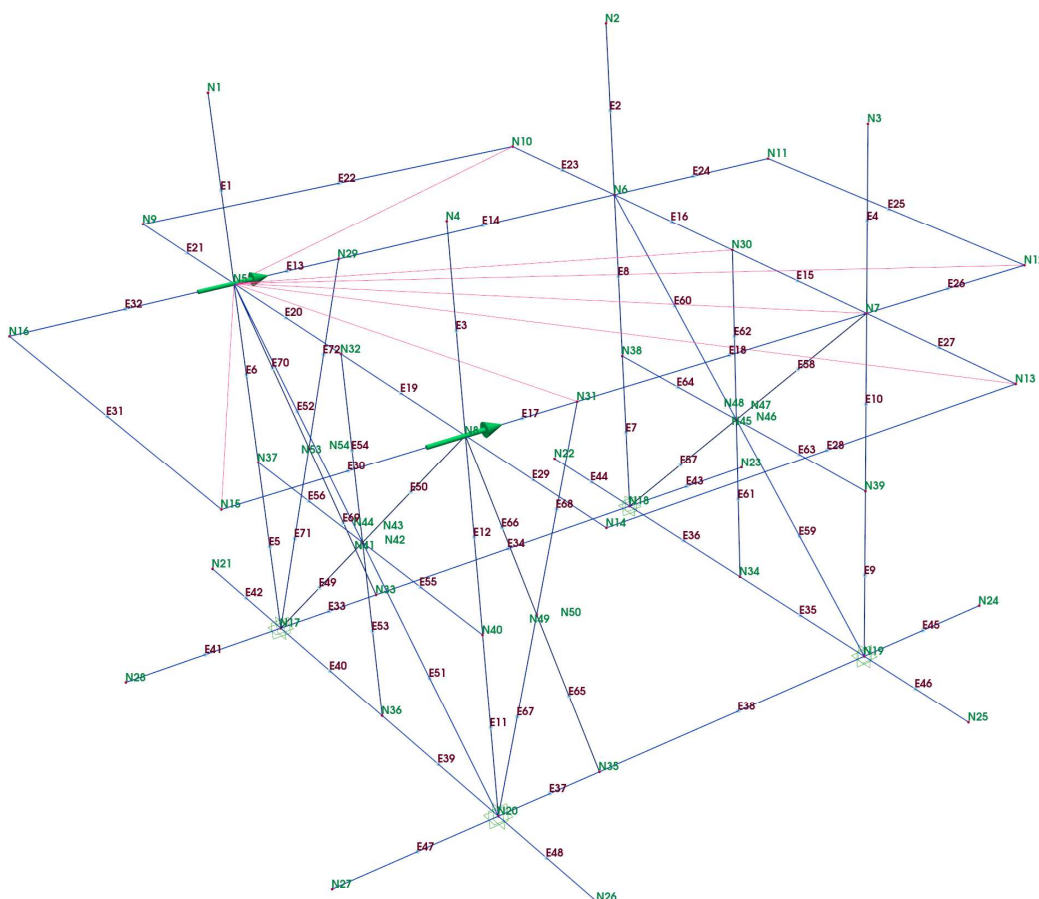


Figure 13 Push over loads location for as built specimen

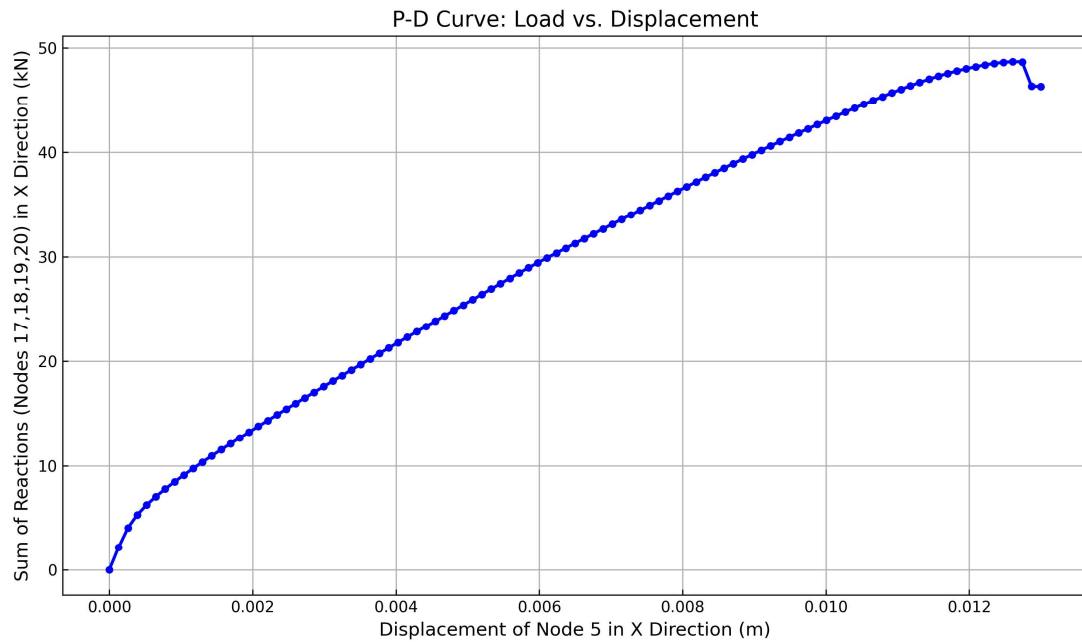


Figure 14 Pushover analysis result for the as-built structure

4 IMPLEMENTATION OF THE DYNAMIC TIME HISTORY (EXCITATION) ON THE AS-BUILT STRUCTURE

The dynamic time history analysis with ReplicaXLite::StructuralAPI was developed in a such a way that cover all basic research needs for advanced dynamic time history analysis following a dynamic pushover approach. That is, ReplicaXLite::StructuralAPI executed successive earthquake excitations while enabling for full results recording in between. After each excitation completion, it updates all model mechanical and dynamic characteristics. In the light of this, users in any interaction need to provide the appropriate time history load (time and acceleration data) in the base structure alongside updated eigenvalues and damping ratio. After each step, the program internally cleans the previous state and prepares the model for the next step. More detailed information will be provided in the upcoming ReplicaXLite software/platform release (Deliverable 4.1) inside the manual guide. The loading protocol follows the setup loading order depicted in Table 3 and reference seismic excitation is provided in Figure 15.

Table 3 Total Test Sequence protocol (11 tests).

Test No.	Name	Type	Intensity	Test No.	Name	Type	Intensity
ST1	WNb0.1g	White noise	0.08g	ST7	WNb0.8g	White noise	0.08g
ST2	EQ0.1g	Earthquake	0.10g	ST8	EQ0.8g	Earthquake	0.80g
ST3	WNb0.2g	White noise	0.08g	ST9	WNb1.1g	White noise	0.08g
ST4	EQ0.2g	Earthquake	0.20g	ST10	EQ1.1g	Earthquake	1.10g
ST5	WNb0.5g	White noise	0.08g	ST11	WNa1.1g	White noise	0.08g
ST6	EQ0.5g	Earthquake	0.50g				

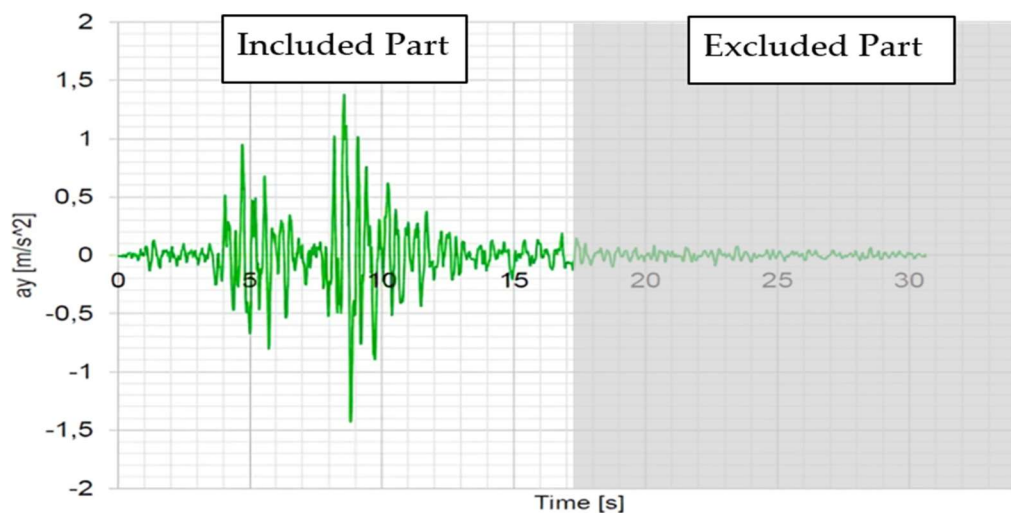


Figure 15 Seismic excitation of original Thessaloniki 1978 earthquake (ay component – Reference Excitation).

Each numerical and analytical result were compared to their relevant counterparts. Summary of the pair comparison is given in Table 4.

Table 4 Experimental and numerical comparison pairs

Sensor	Name	Numerical Nodes	Sensor	Name	Numerical Nodes
Draw-Wire	W1	12	Accelerometer	Acc1	12
Draw-Wire	W2	11	Accelerometer	Acc4	11

Sensor	Name	Numerical Nodes	Sensor	Name	Numerical Nodes
Draw-Wire	W3	24	Accelerometer	Acc7	45, 46, 47, 48
Draw-Wire	W4	23	Accelerometer	Acc10	34,19,18

4.1 ST2::EQ0.1G RESULTS

The result for draw-wires and accelerometers for ST2::EQ0.1g are presented here.

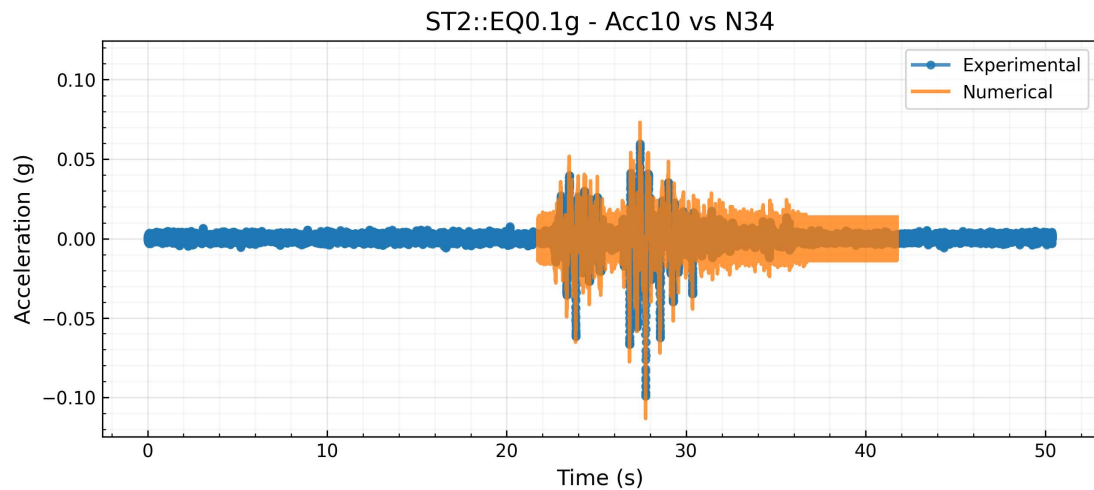


Figure 16 ST2 - Acceleration comparison Acc10 vs N34

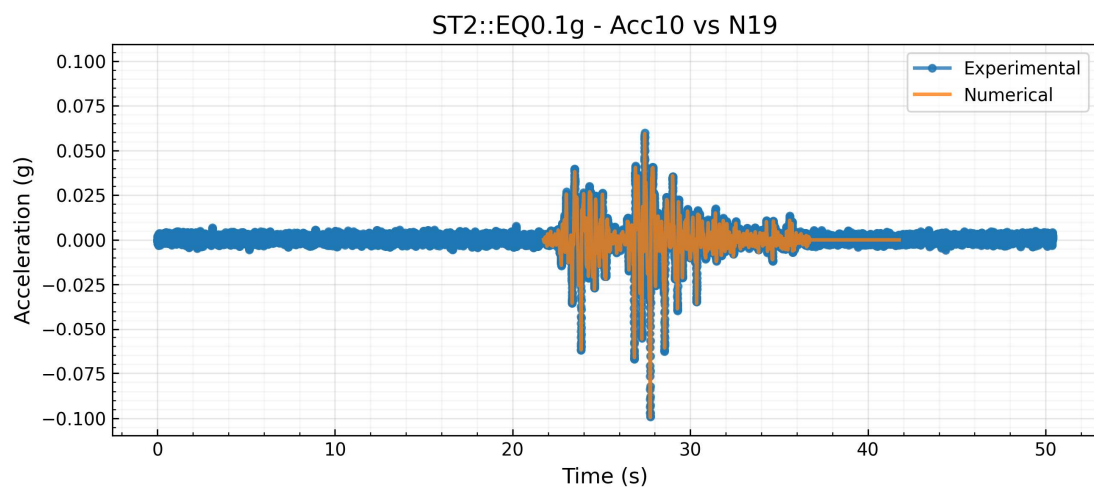


Figure 17 ST2 - Acceleration comparison Acc10 vs N19

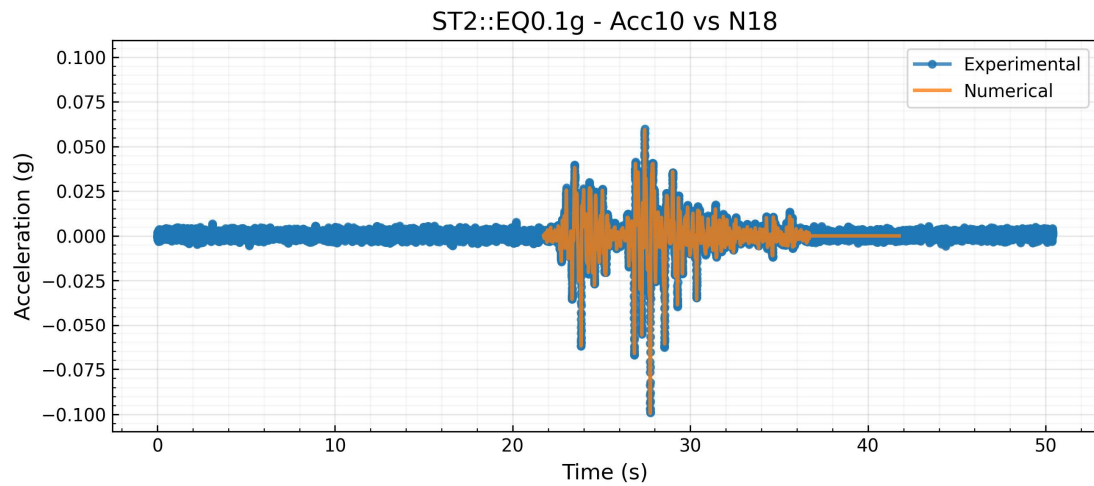
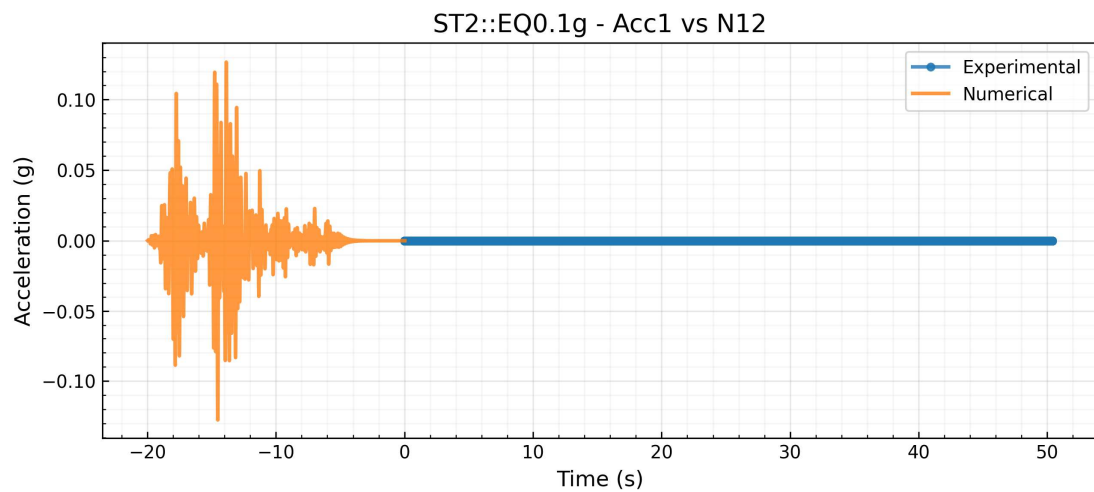


Figure 18 ST2 - Acceleration comparison Acc10 vs N18



Acc1 Record Not Available

Figure 19 ST2 - Acceleration comparison Acc1 vs N12

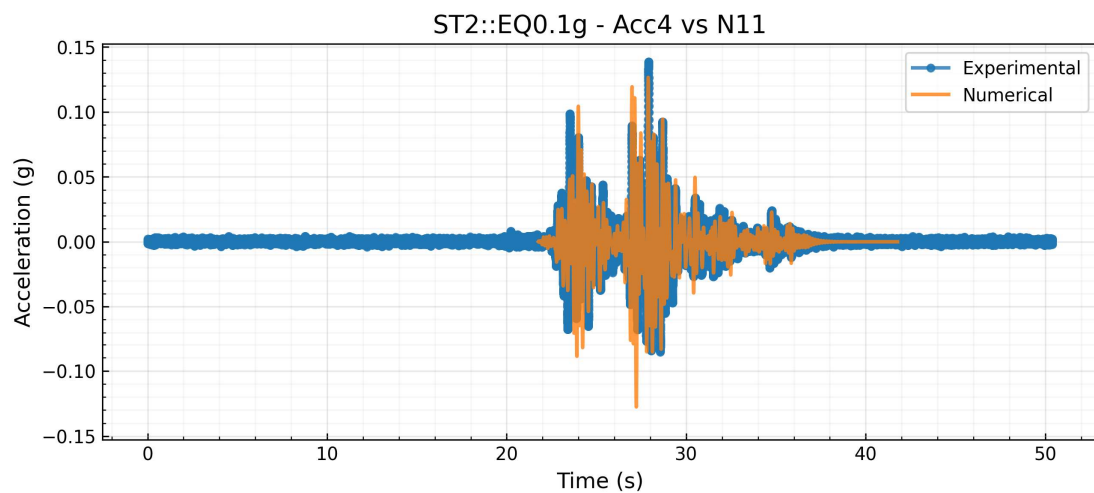


Figure 20 ST2 - Acceleration comparison Acc4 vs N11

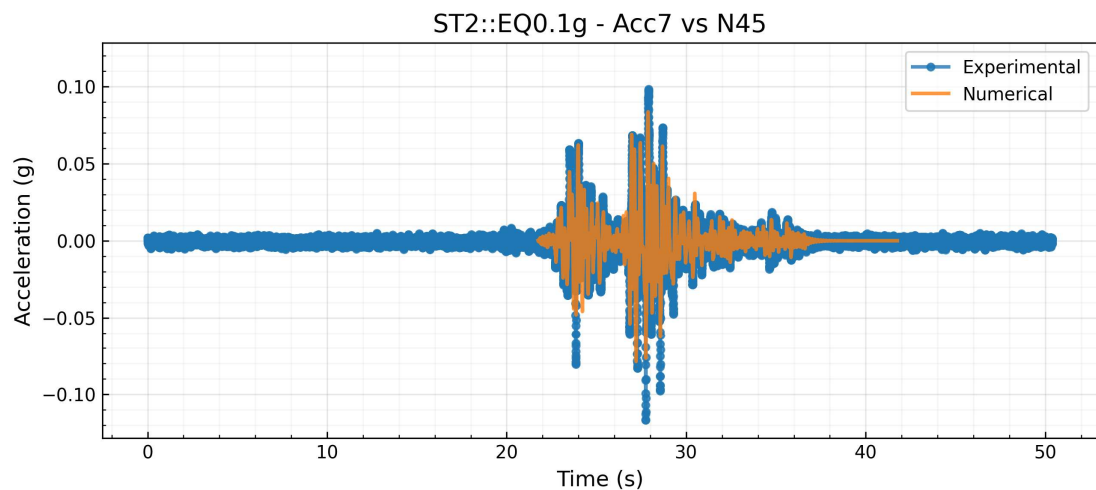


Figure 21 ST2 - Acceleration comparison Acc7 vs N45

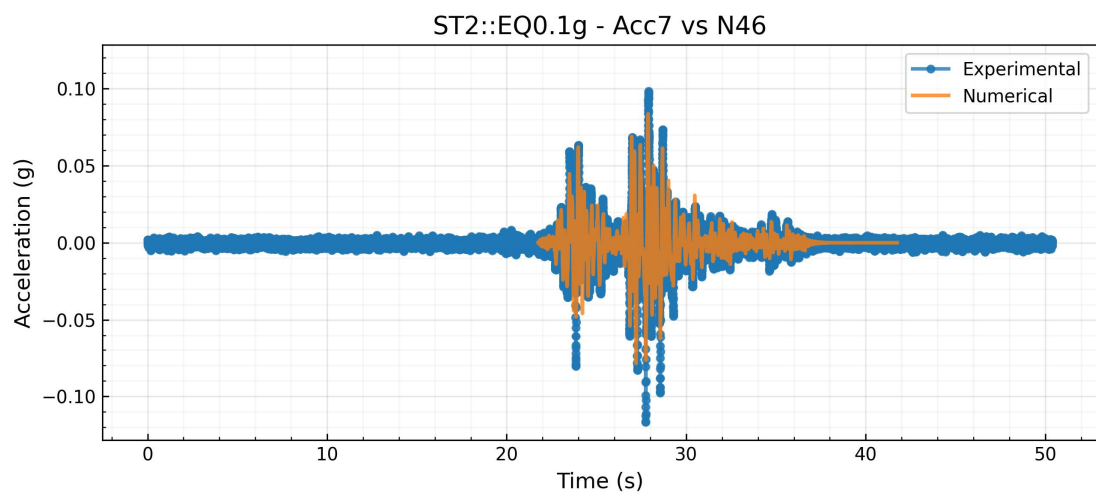


Figure 22 ST2 - Acceleration comparison Acc7 vs N46

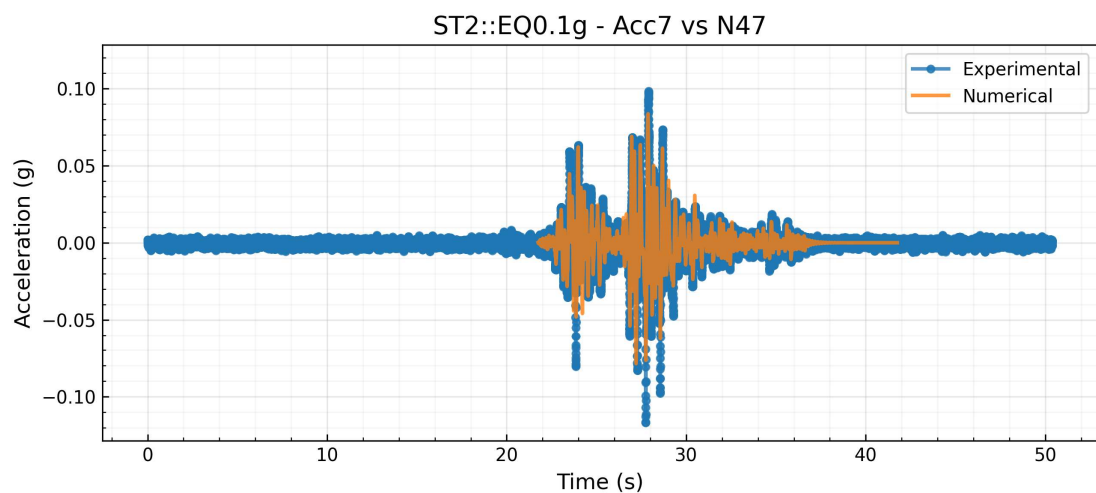


Figure 23 ST2 - Acceleration comparison Acc7 vs N47

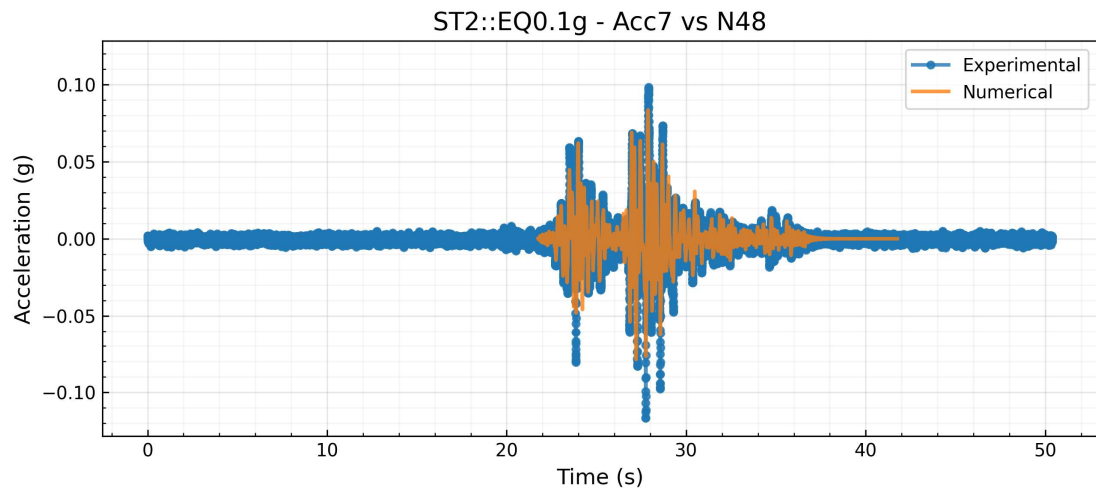


Figure 24 ST2 - Acceleration comparison Acc7 vs N48

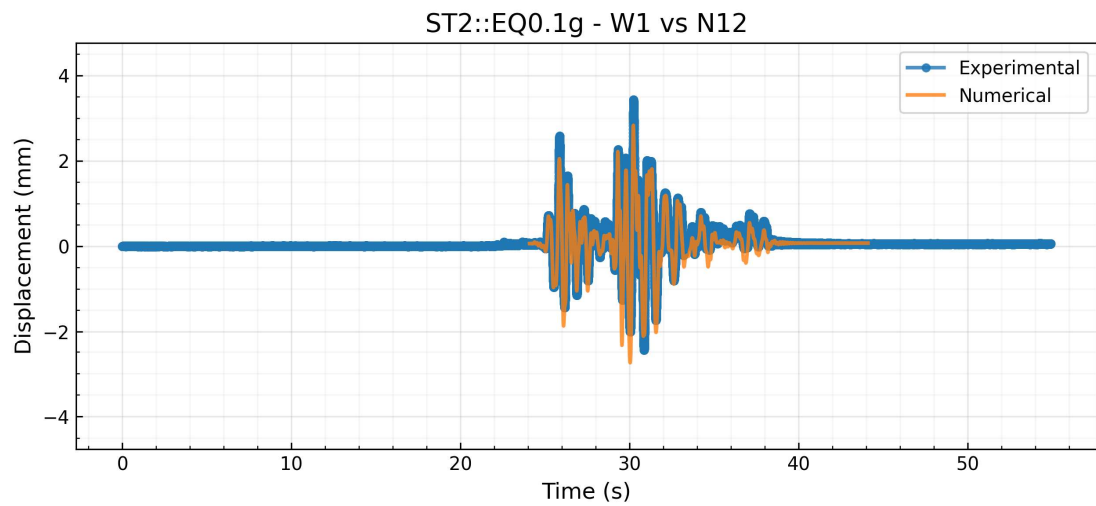


Figure 25 ST2 - Displacement comparison W1 vs N12

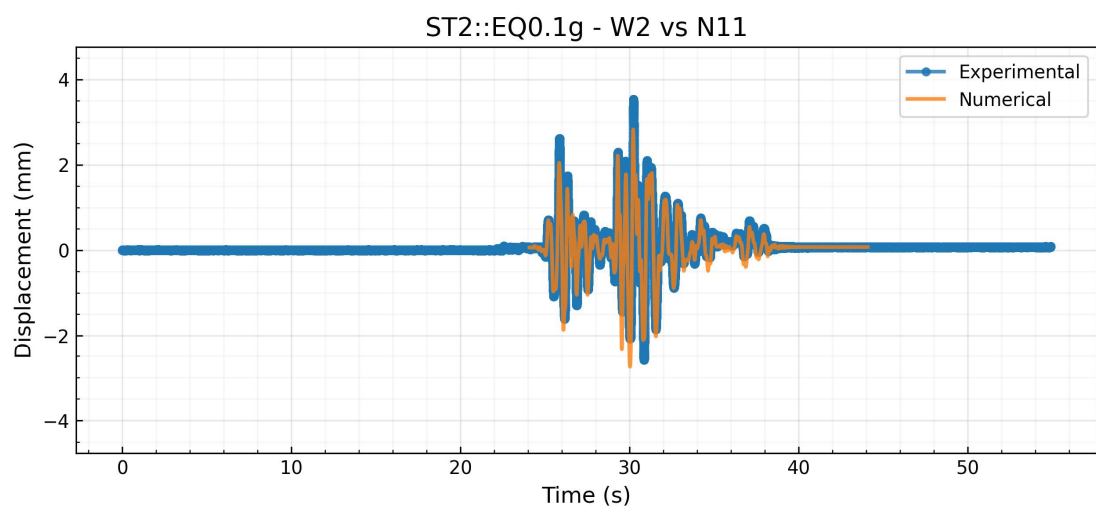


Figure 26 ST2 - Displacement comparison W2 vs N11

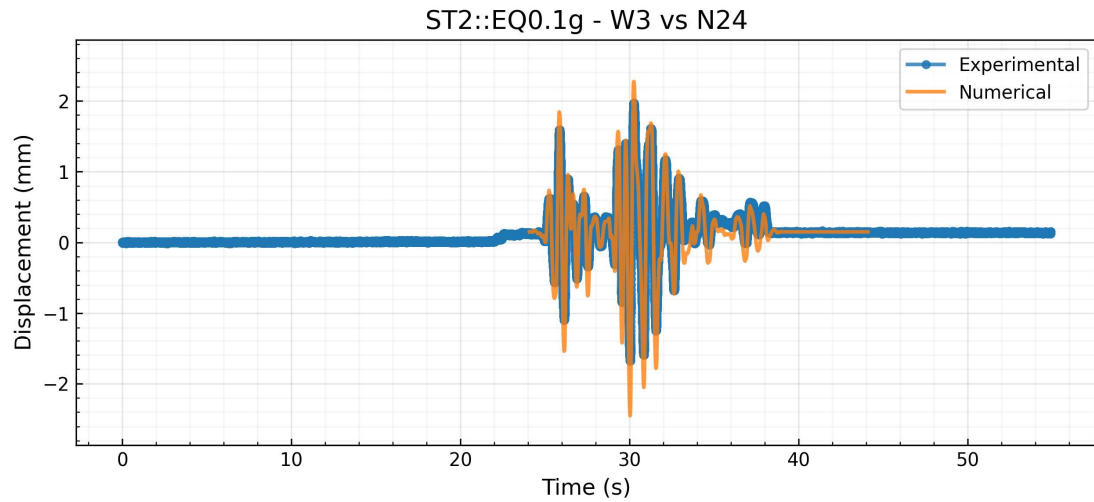


Figure 27 ST2 - Displacement comparison W3 vs N24

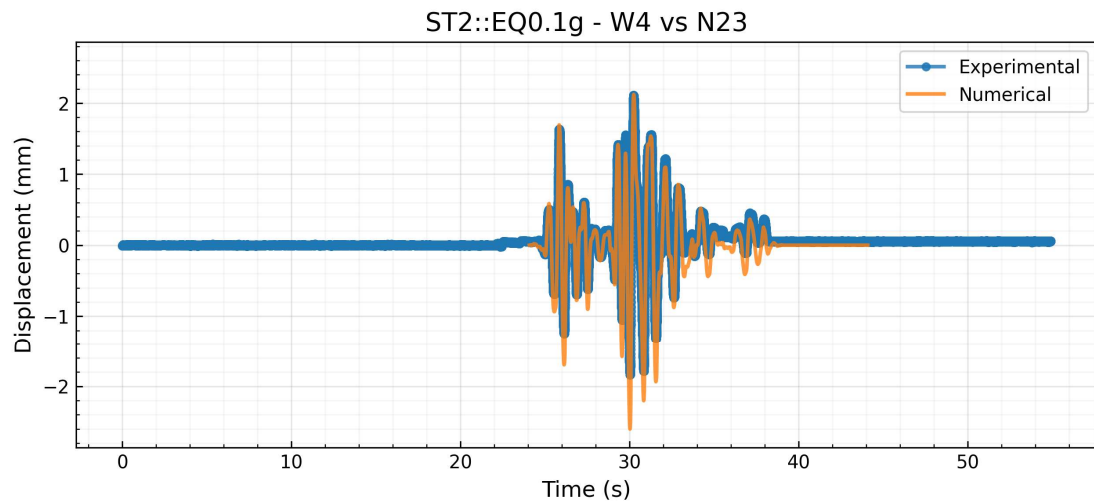


Figure 28 ST2 - Displacement comparison W4 vs N23

4.2 ST4::EQ0.2G RESULTS

The result for draw-wires and accelerometers for ST4::EQ0.2g are presented here.

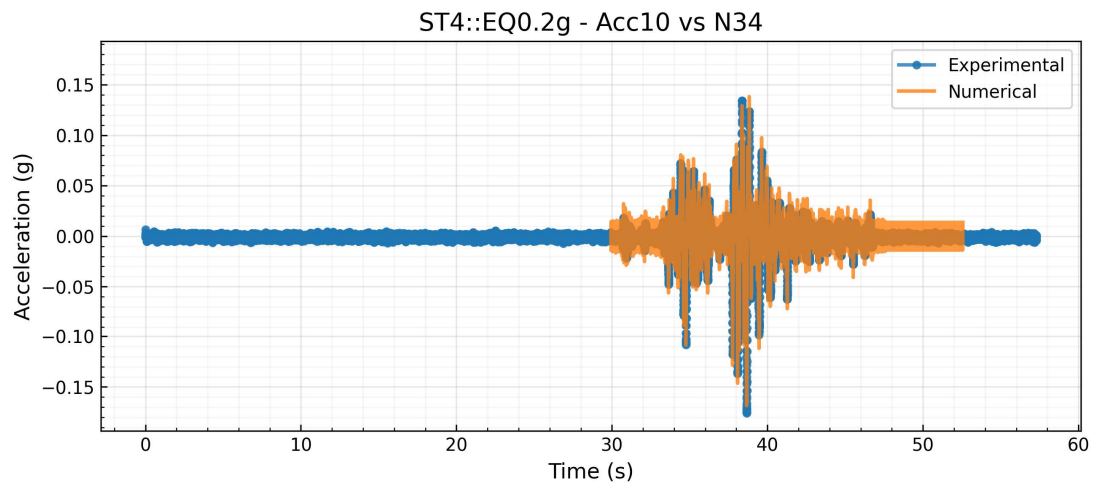


Figure 29 ST4 - Acceleration comparison Acc10 vs N34

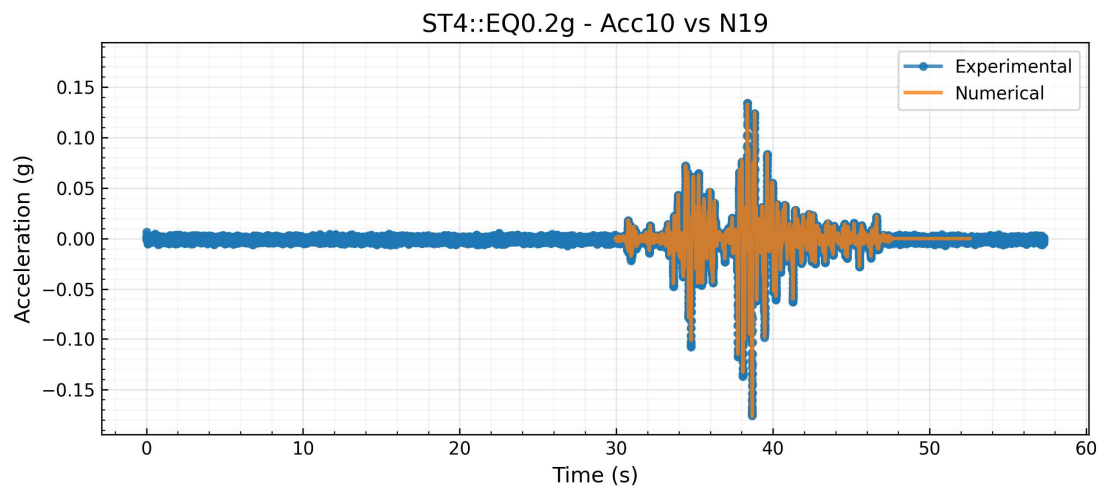


Figure 30 ST4 - Acceleration comparison Acc10 vs N19

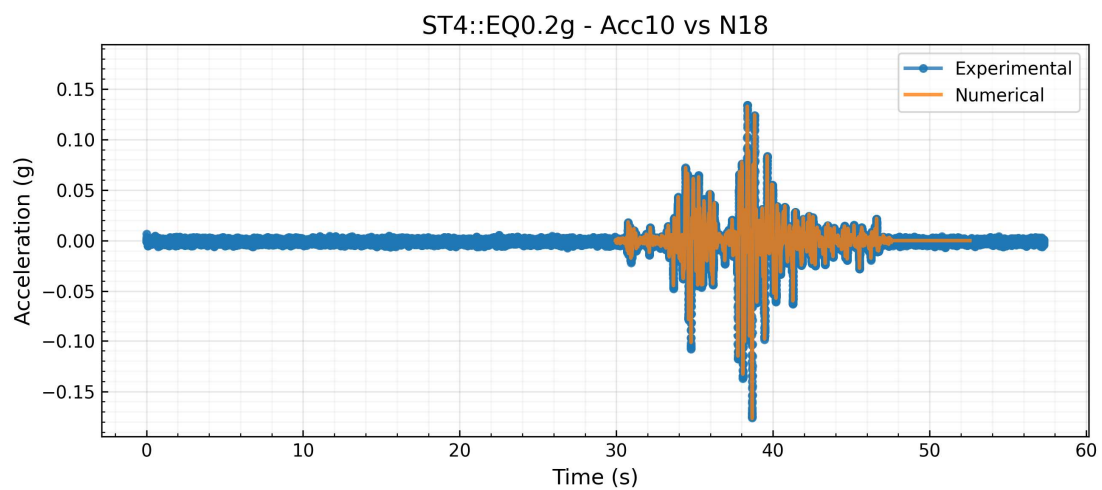


Figure 31 ST4 - Acceleration comparison Acc10 vs N18

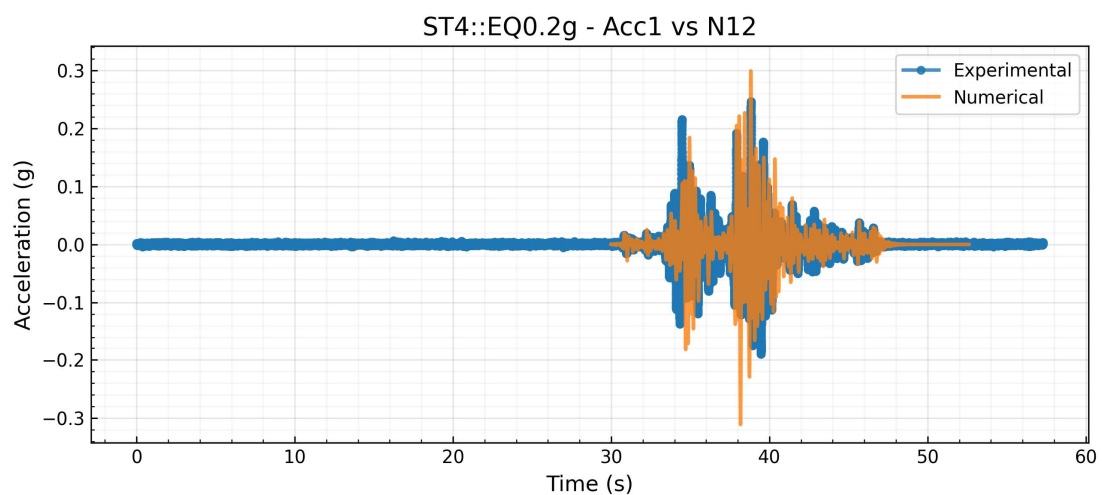


Figure 32 ST4 - Acceleration comparison Acc1 vs N12

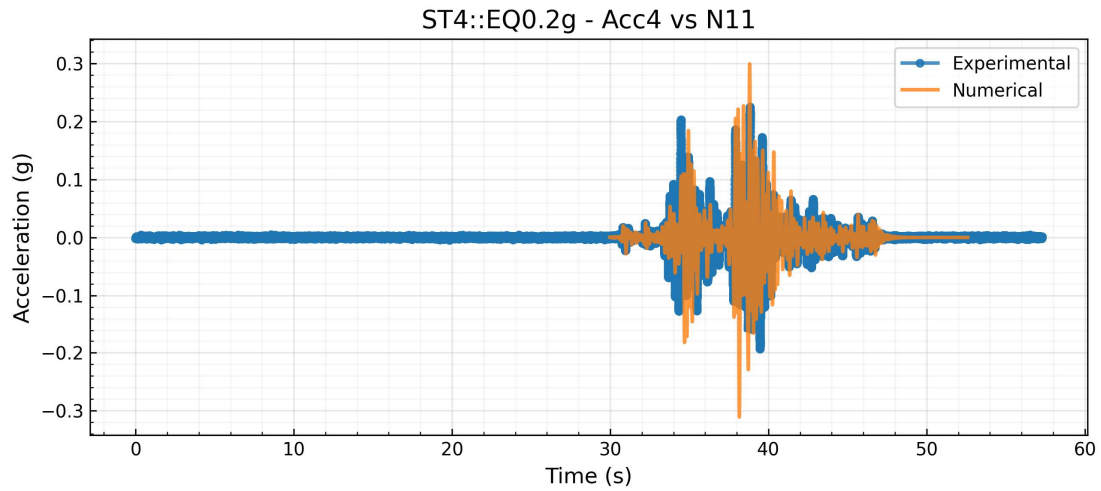


Figure 33 ST4 - Acceleration comparison Acc4 vs N11

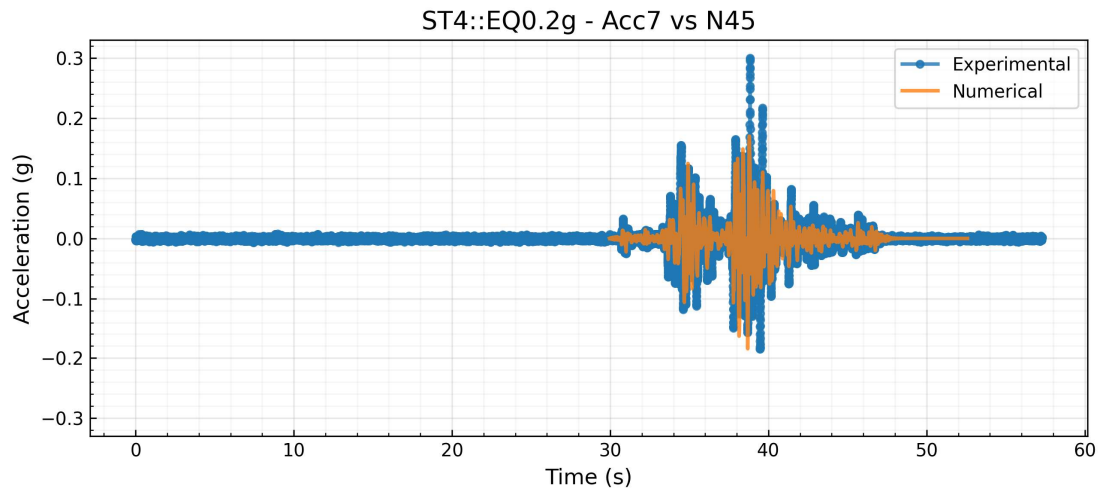


Figure 34 ST4 - Acceleration comparison Acc7 vs N45

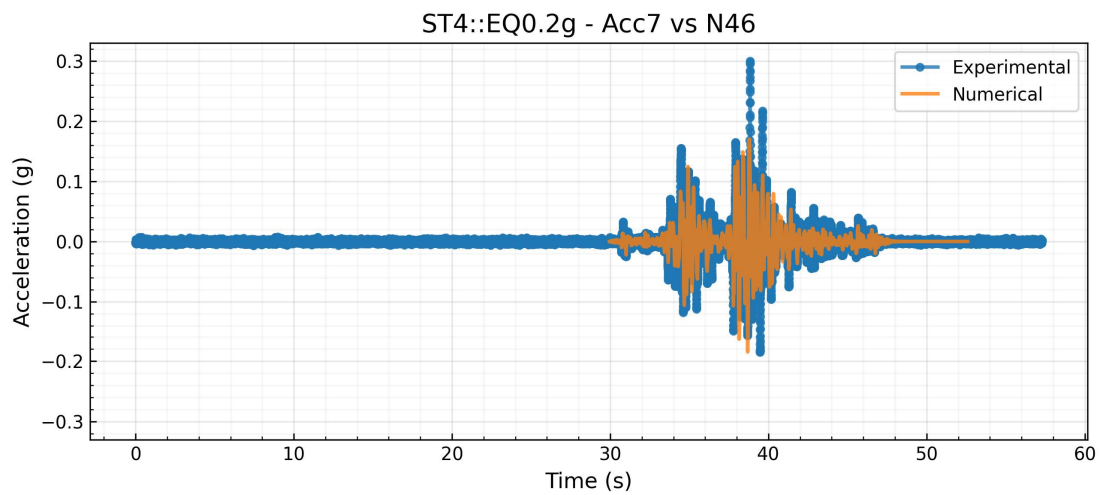


Figure 35 ST4 - Acceleration comparison Acc7 vs N46

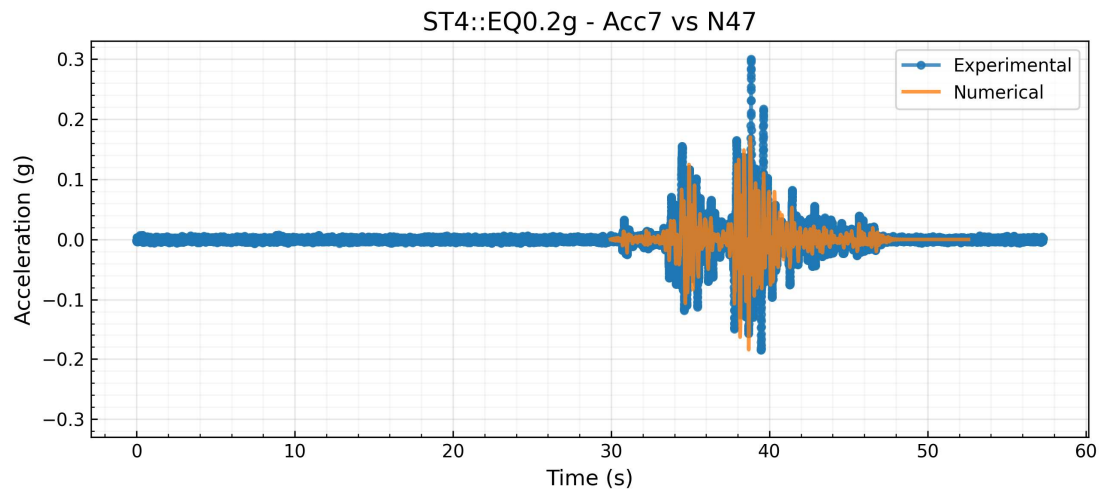


Figure 36 ST4 - Acceleration comparison Acc7 vs N47

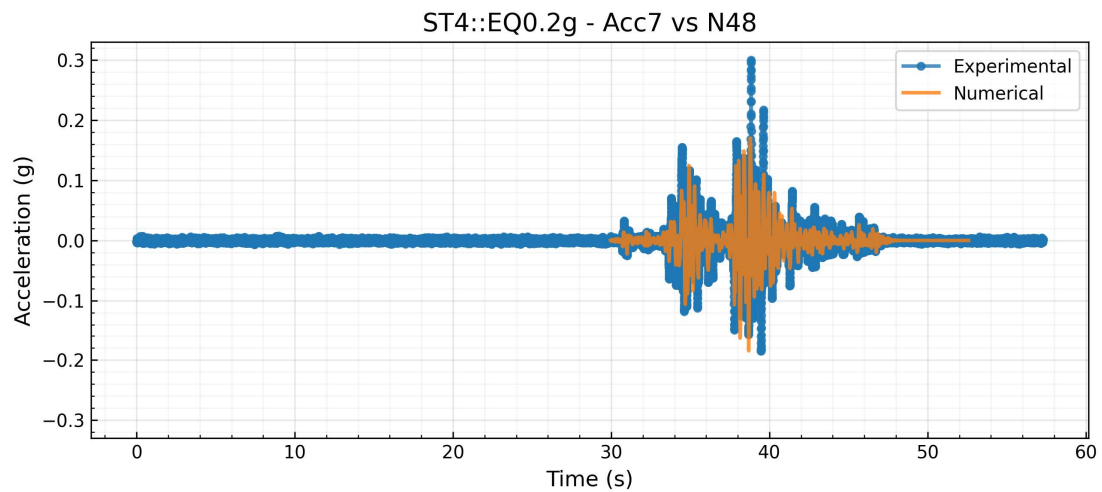


Figure 37 ST4 - Acceleration comparison Acc7 vs N48

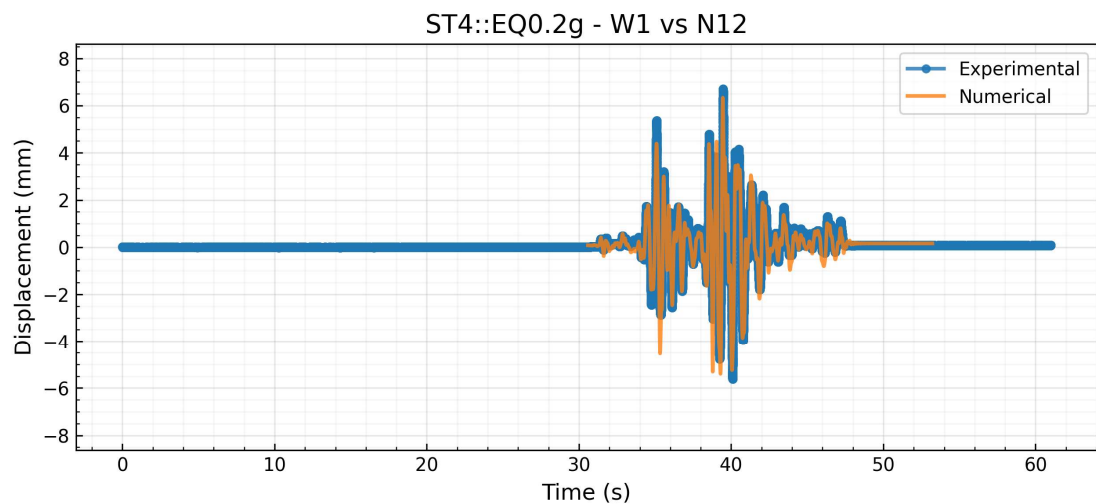


Figure 38 ST4 - Displacement comparison W1 vs N12

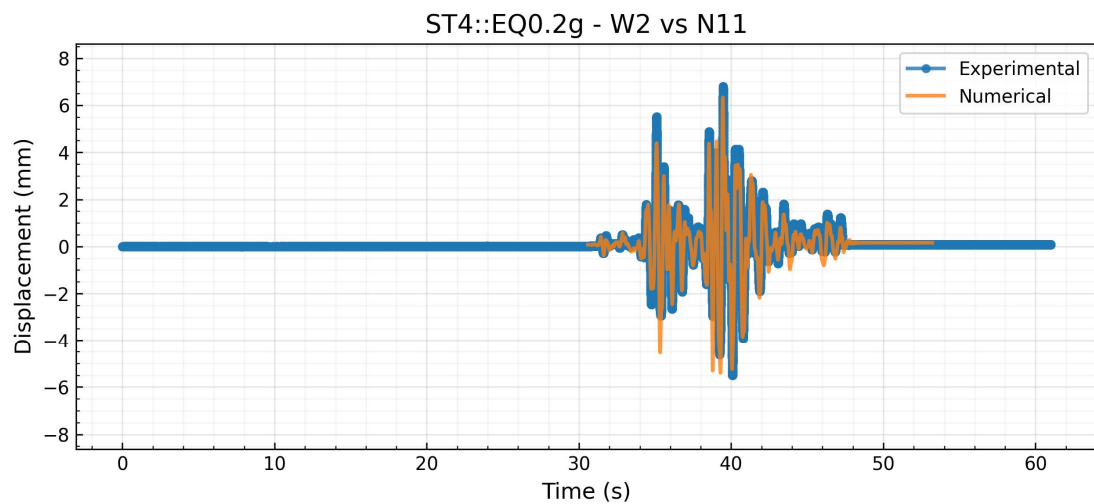


Figure 39 ST4 - Displacement comparison W2 vs N11

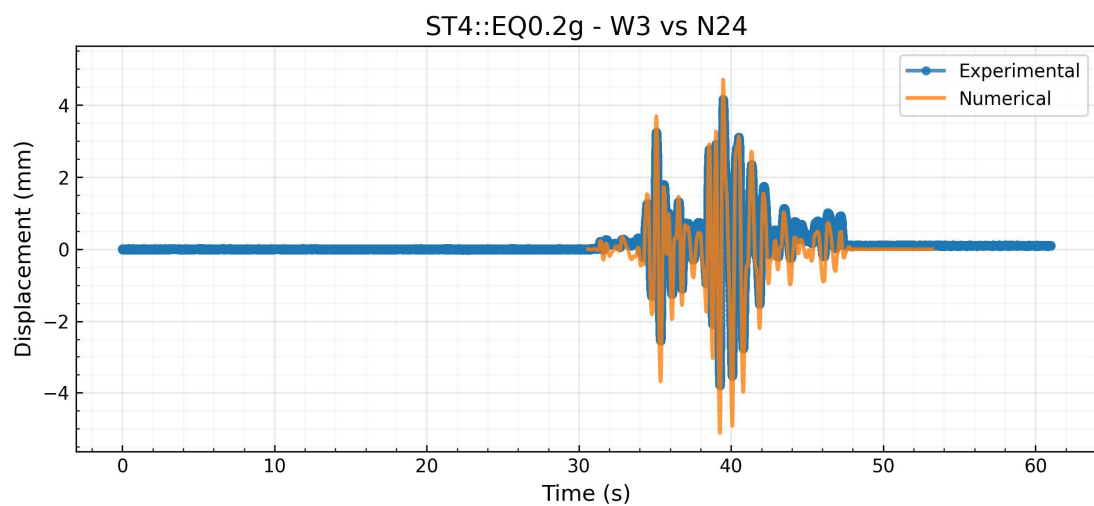


Figure 40 ST4 - Displacement comparison W3 vs N24

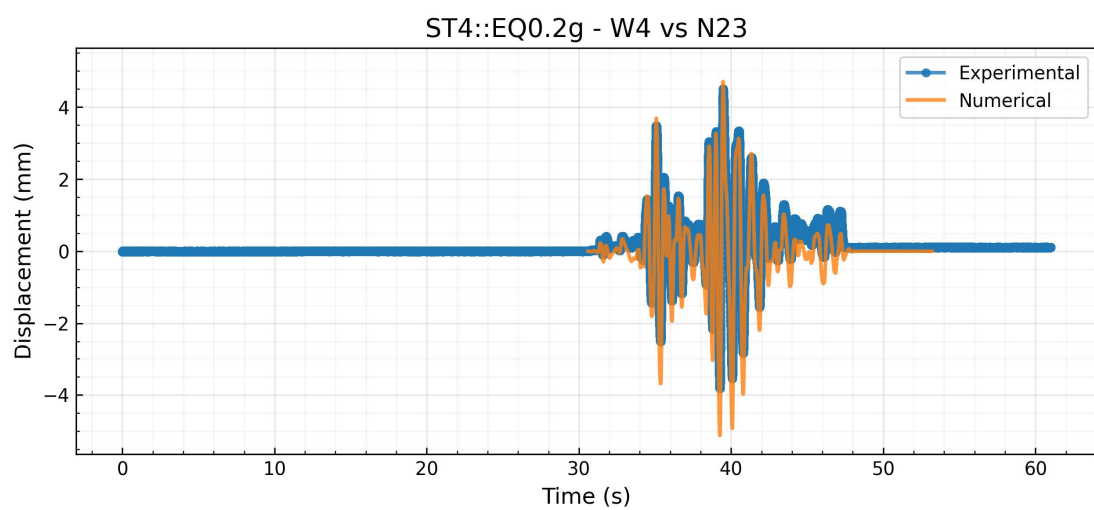


Figure 41 ST4 - Displacement comparison W4 vs N23

4.3 ST6::EQ0.5G RESULTS

The result for draw-wires and accelerometers for ST6::EQ0.5g are presented here.

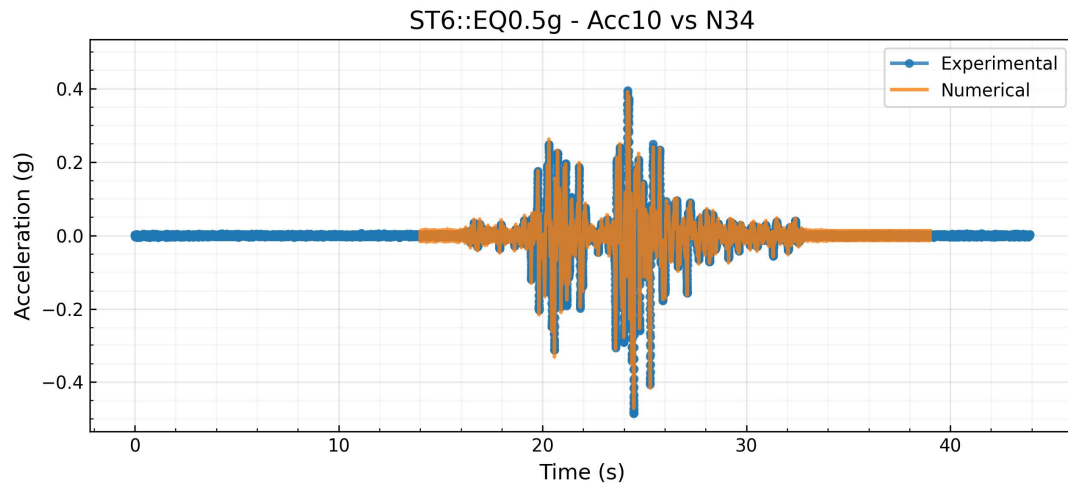


Figure 42 ST6 - Acceleration comparison Acc10 vs N34

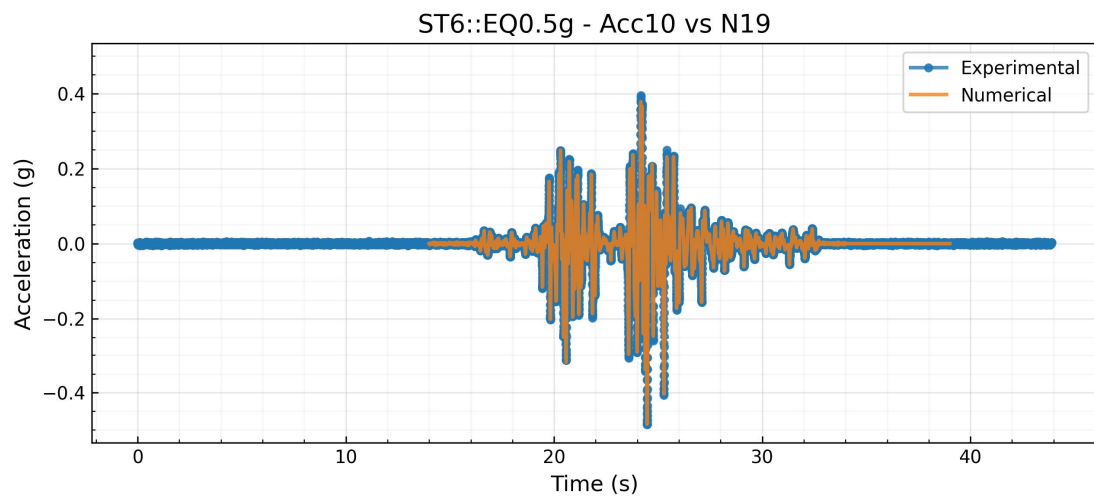


Figure 43 ST6 - Acceleration comparison Acc10 vs N19

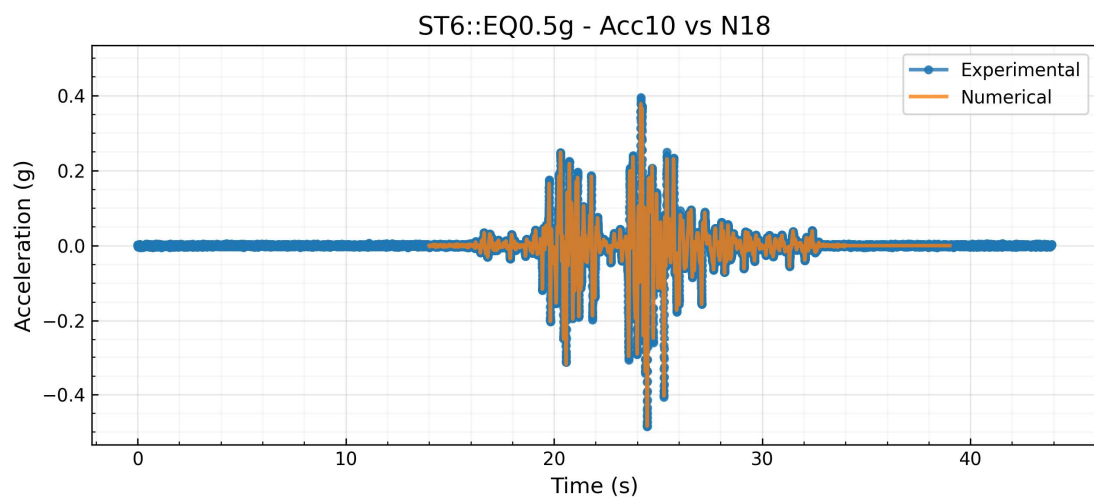


Figure 44 ST6 - Acceleration comparison Acc10 vs N18

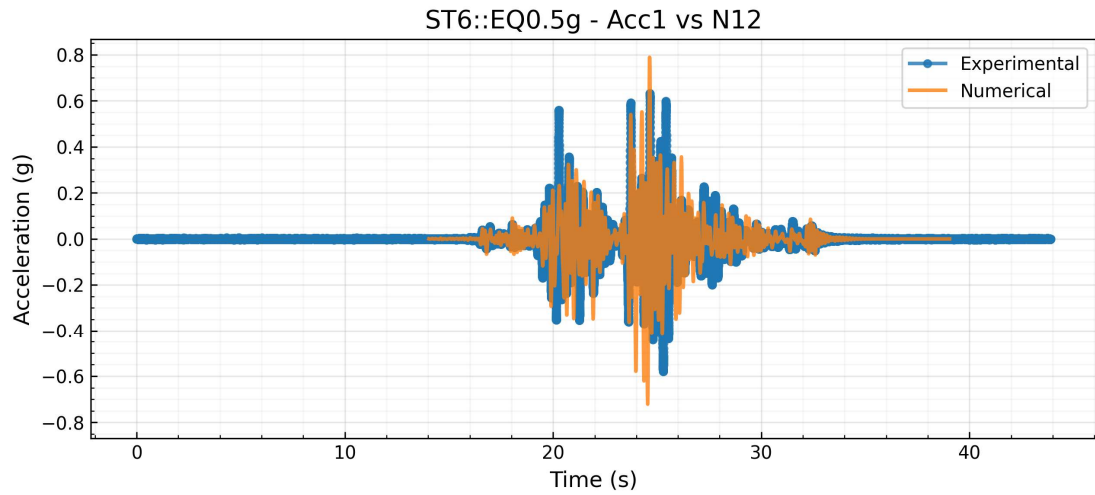


Figure 45 ST6 - Acceleration comparison Acc1 vs N12

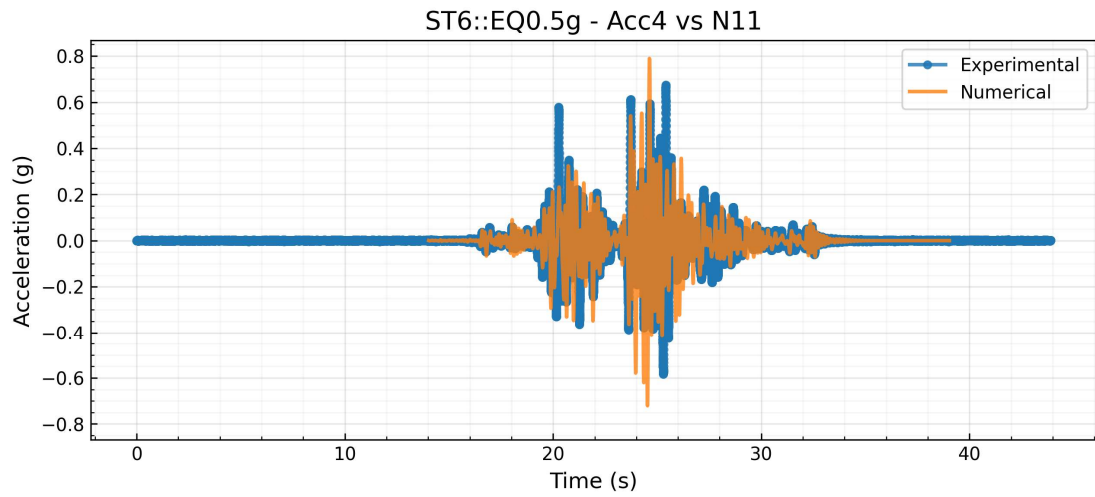


Figure 46 ST6 - Acceleration comparison Acc4 vs N11

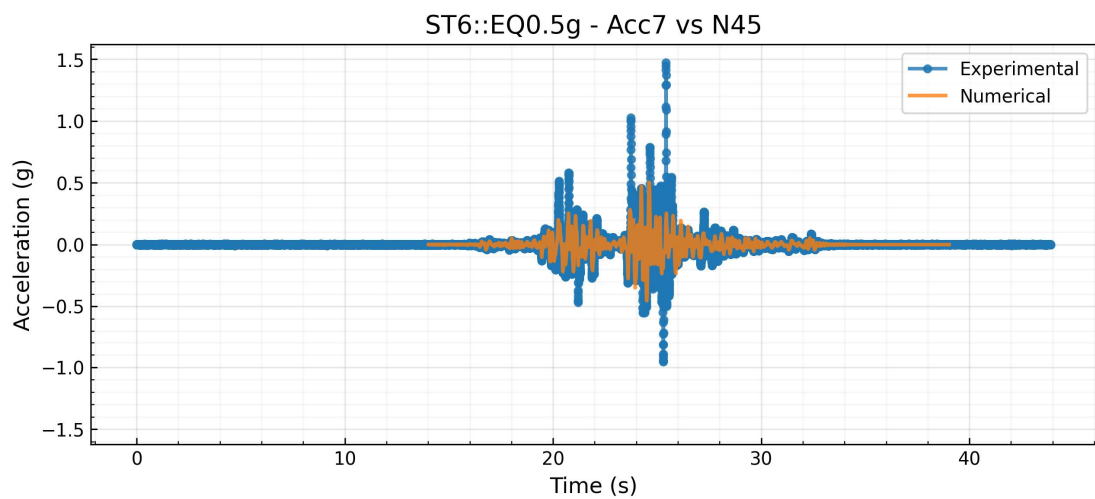


Figure 47 ST6 - Acceleration comparison Acc7 vs N45

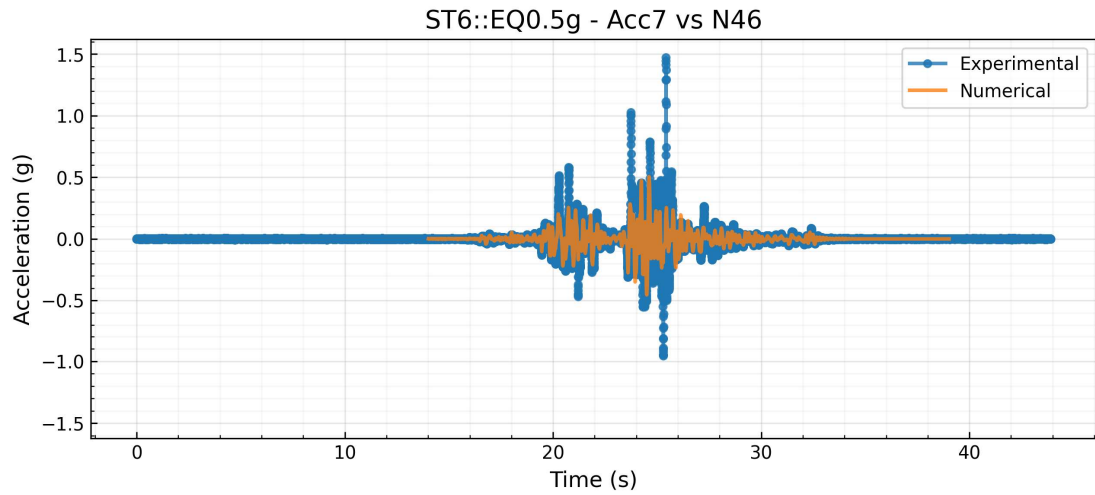


Figure 48 ST6 - Acceleration comparison Acc7 vs N46

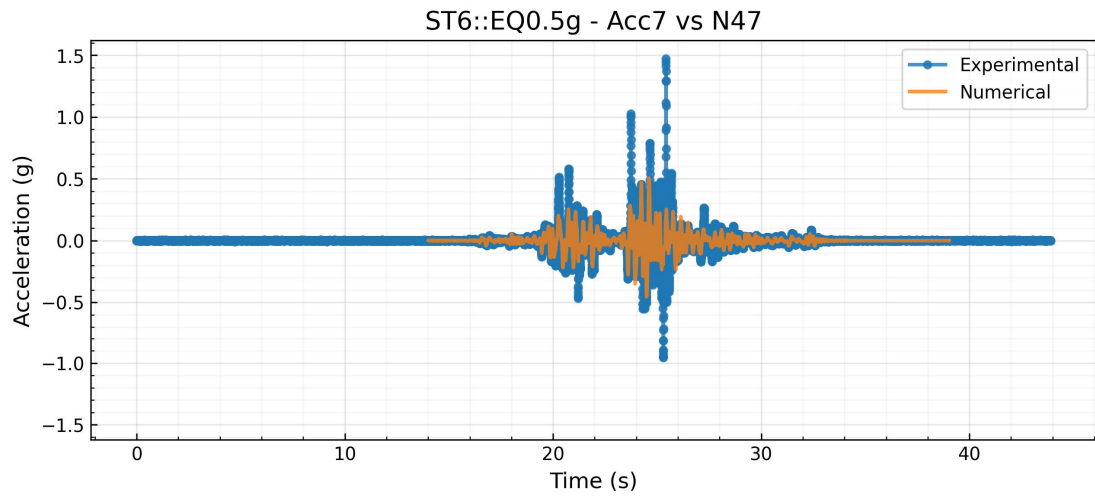


Figure 49 ST6 - Acceleration comparison Acc7 vs N47

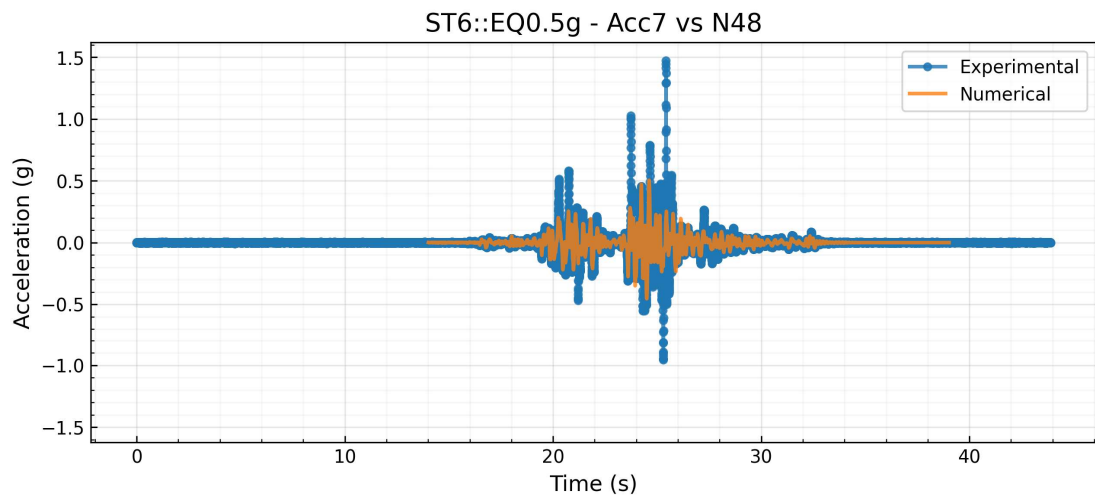


Figure 50 ST6 - Acceleration comparison Acc7 vs N48

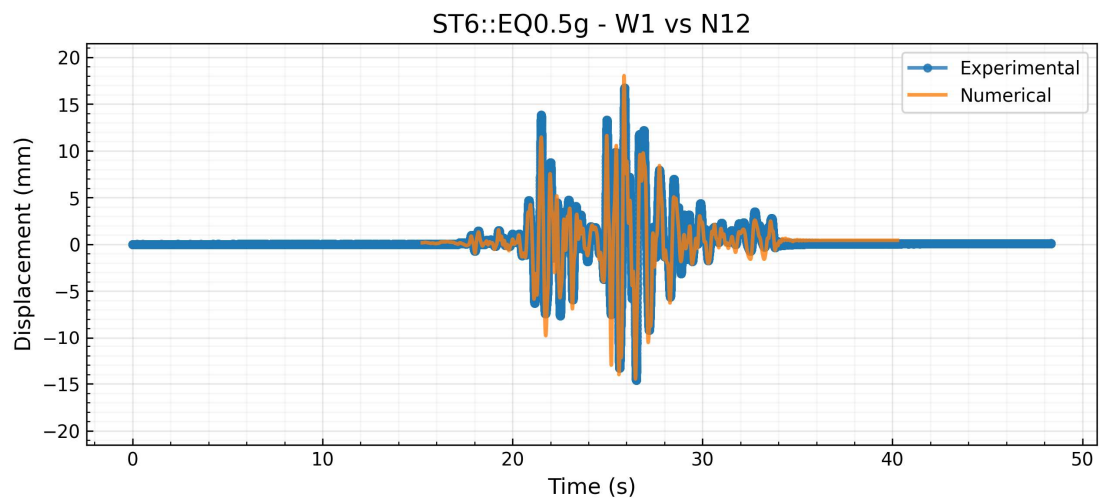


Figure 51 ST6 - Displacement comparison W1 vs N12

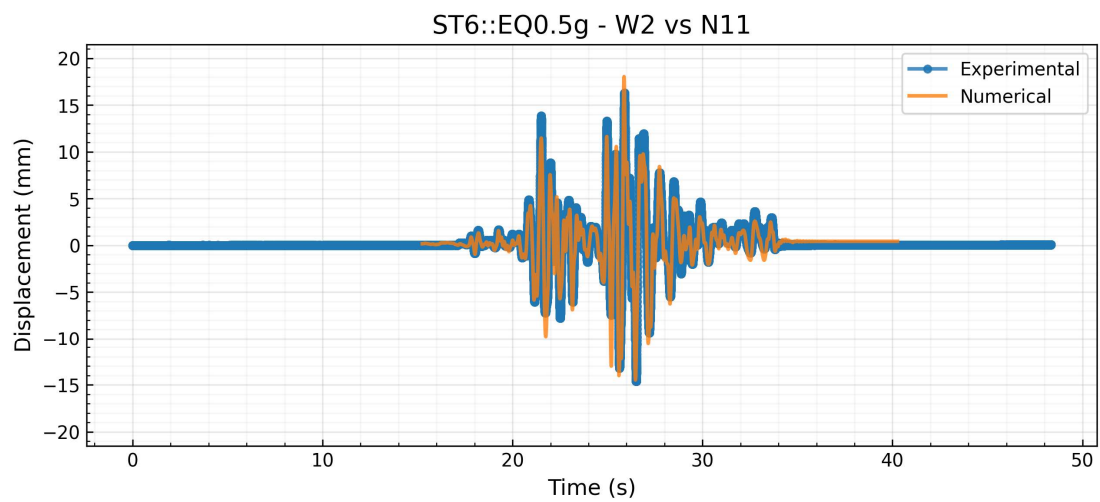


Figure 52 ST6 - Displacement comparison W2 vs N11

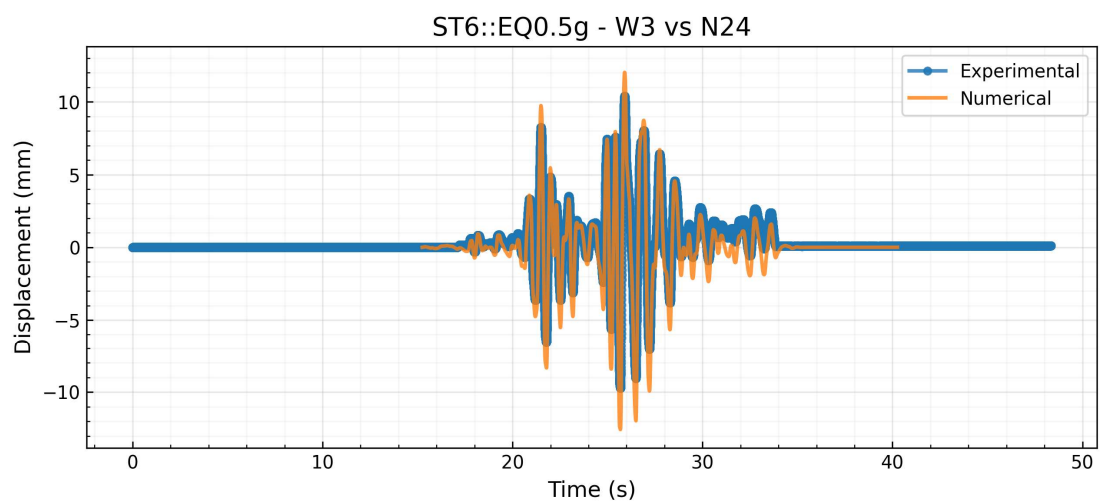


Figure 53 ST6 - Displacement comparison W3 vs N24

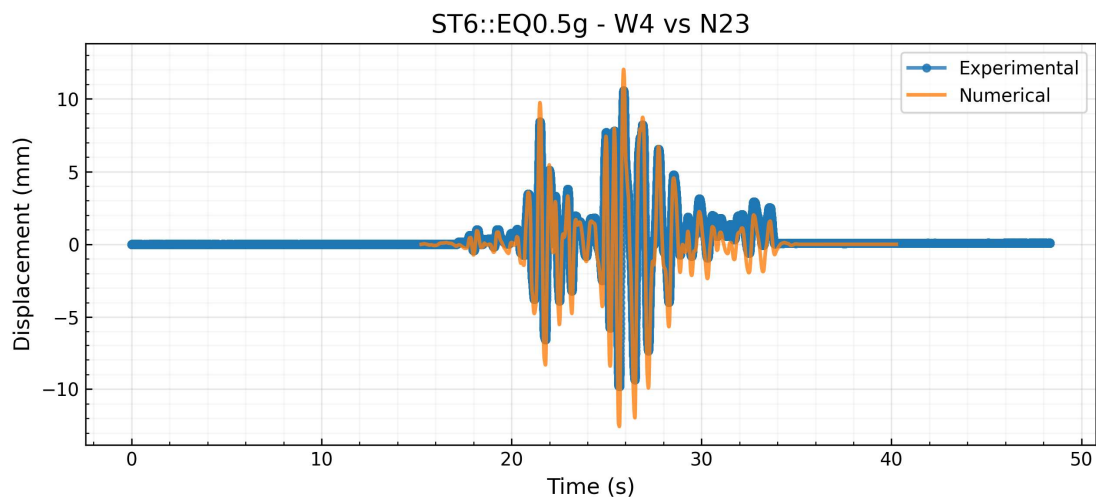


Figure 54 ST6 - Displacement comparison W4 vs N23

4.4 ST8::EQ0.8G RESULTS

The result for draw-wires and accelerometers for ST8::EQ0.8g are presented here.

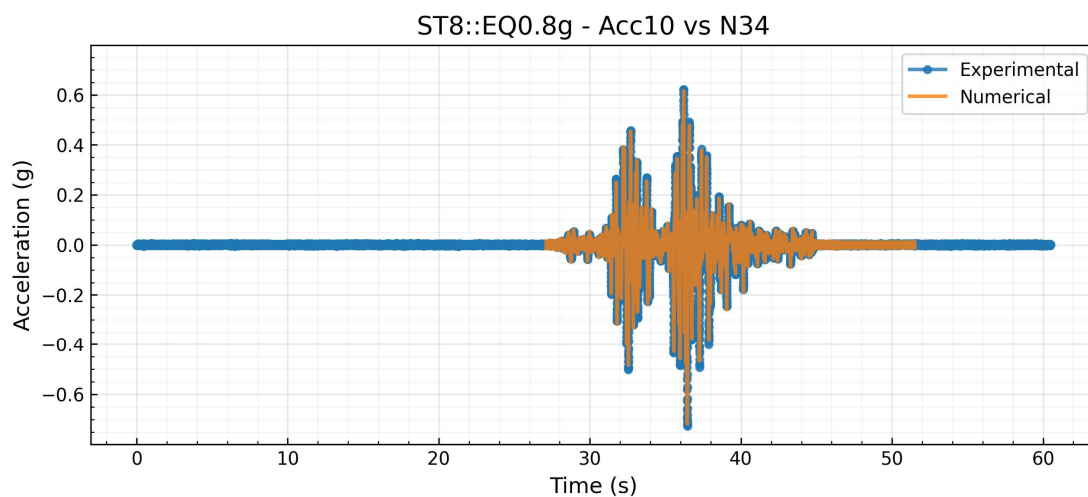


Figure 55 ST8 - Acceleration comparison Acc10 vs N34

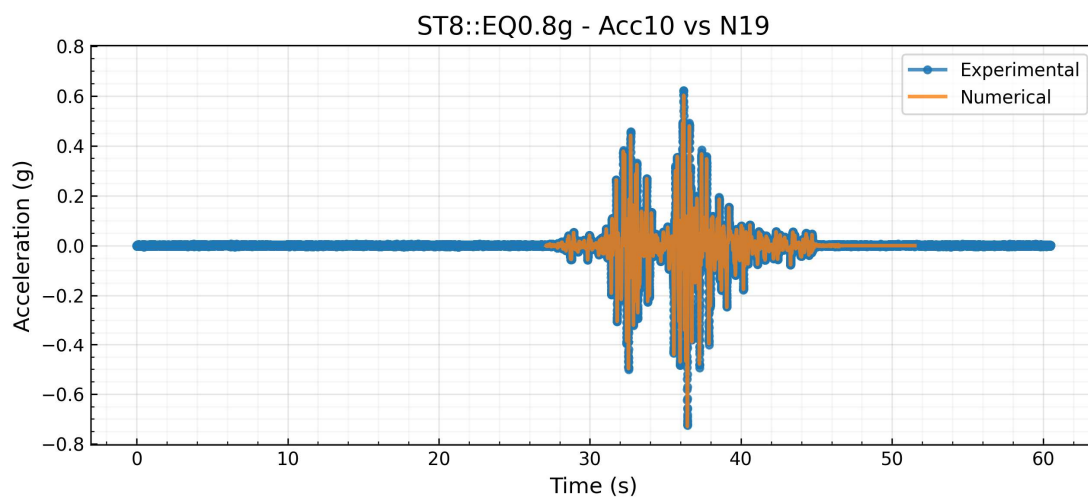


Figure 56 ST8 - Acceleration comparison Acc10 vs N19

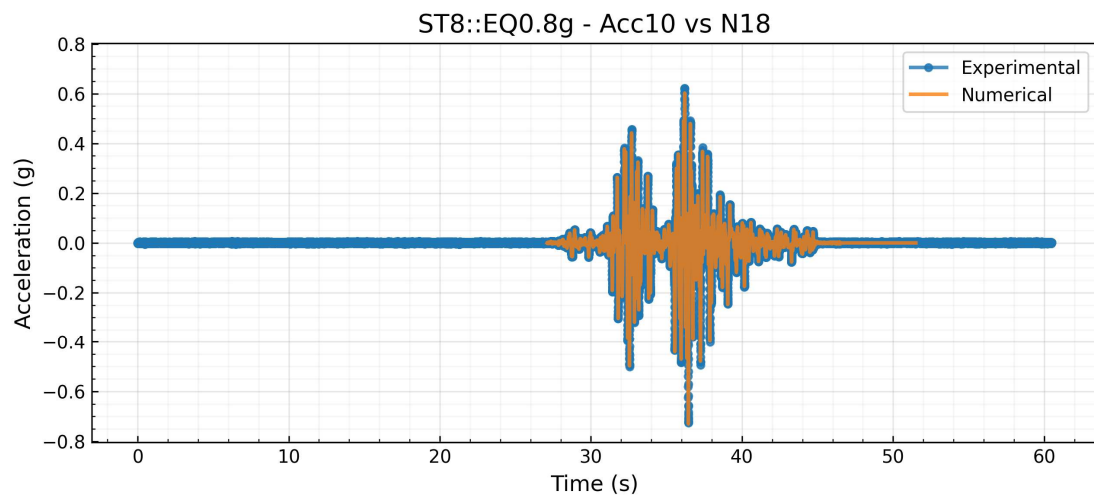


Figure 57 ST8 - Acceleration comparison Acc10 vs N18

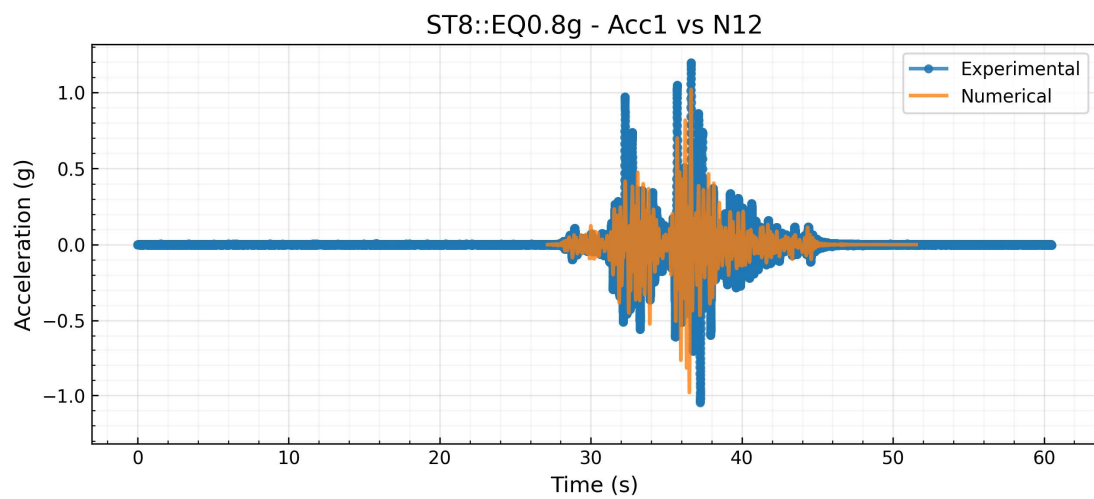


Figure 58 ST8 - Acceleration comparison Acc1 vs N12

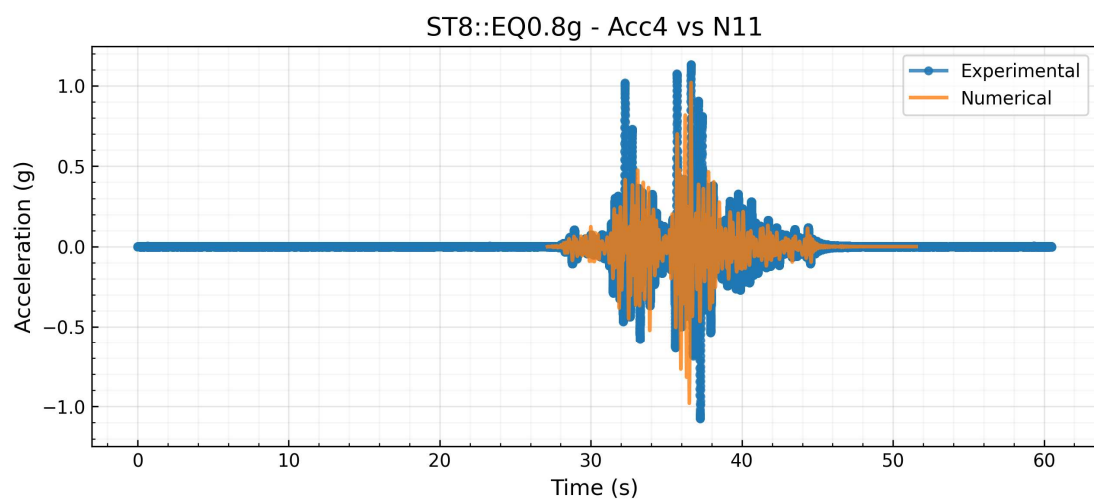


Figure 59 ST8 - Acceleration comparison Acc4 vs N11

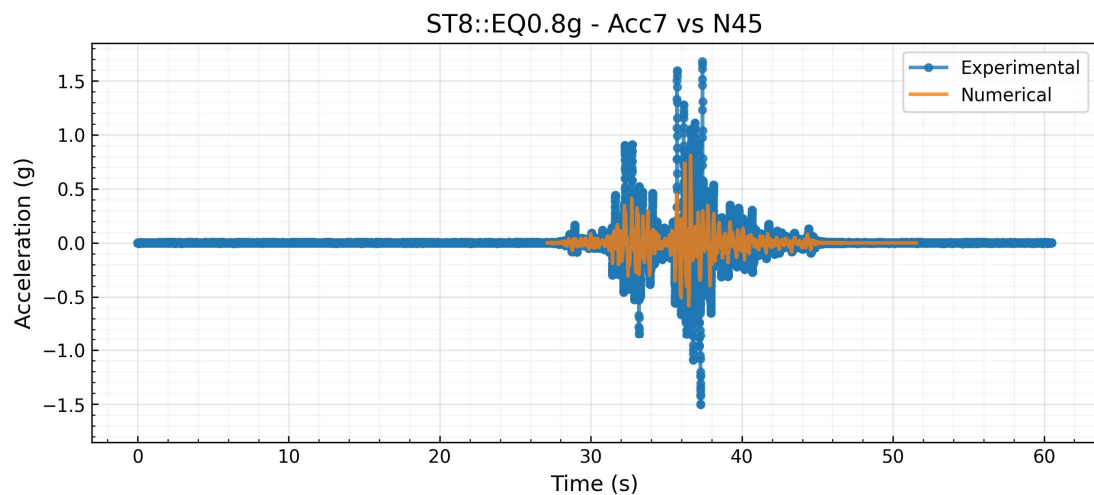


Figure 60 ST8 - Acceleration comparison Acc7 vs N45

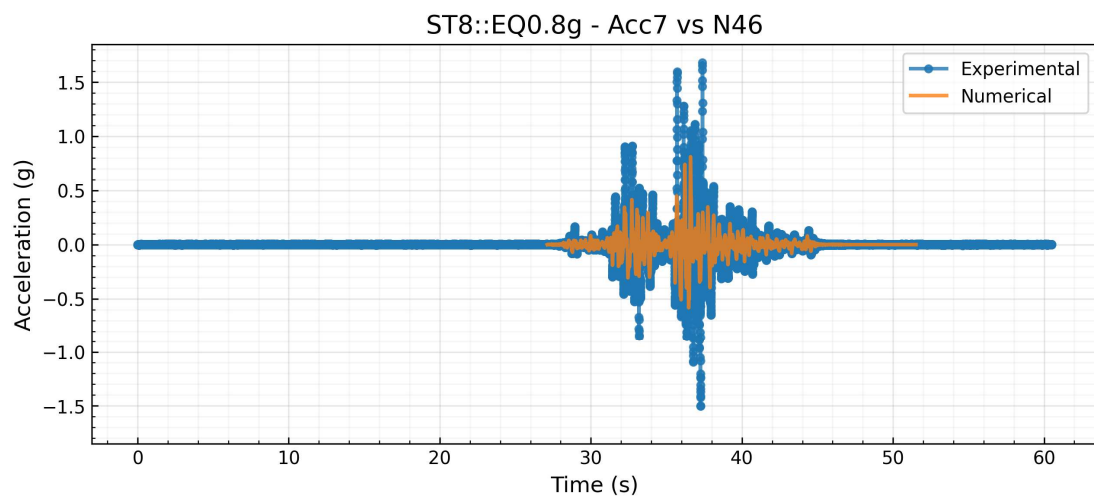


Figure 61 ST8 - Acceleration comparison Acc7 vs N46

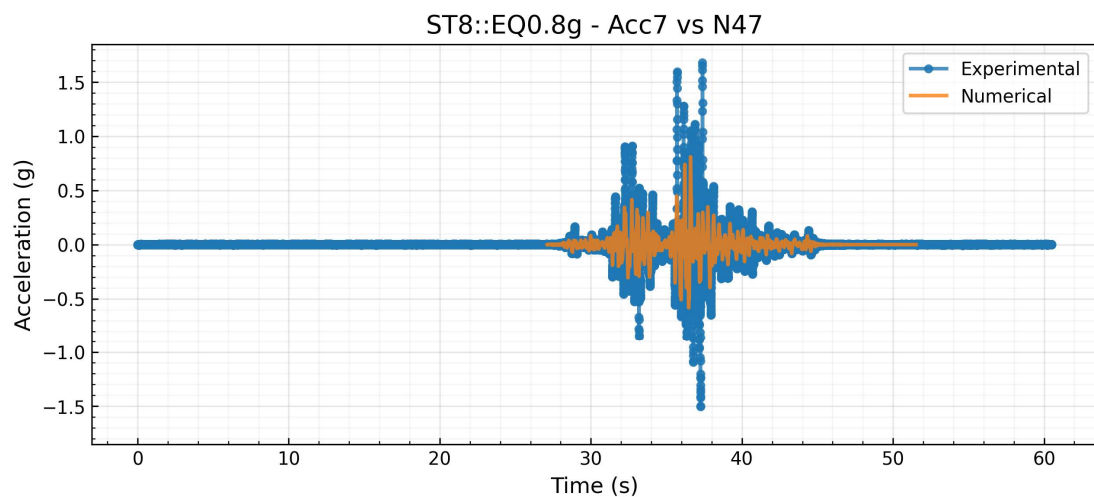


Figure 62 ST8 - Acceleration comparison Acc7 vs N47

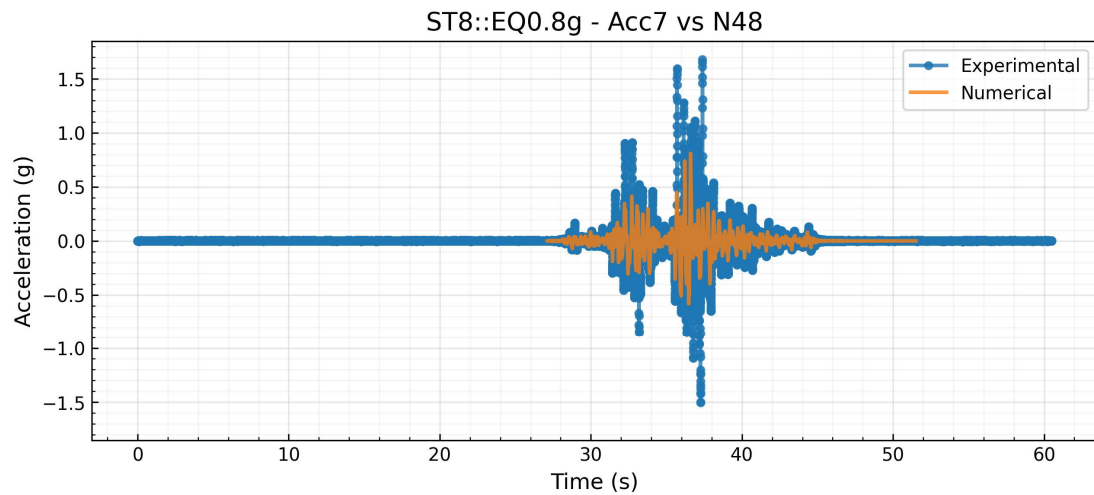


Figure 63 ST8 - Acceleration comparison Acc7 vs N48

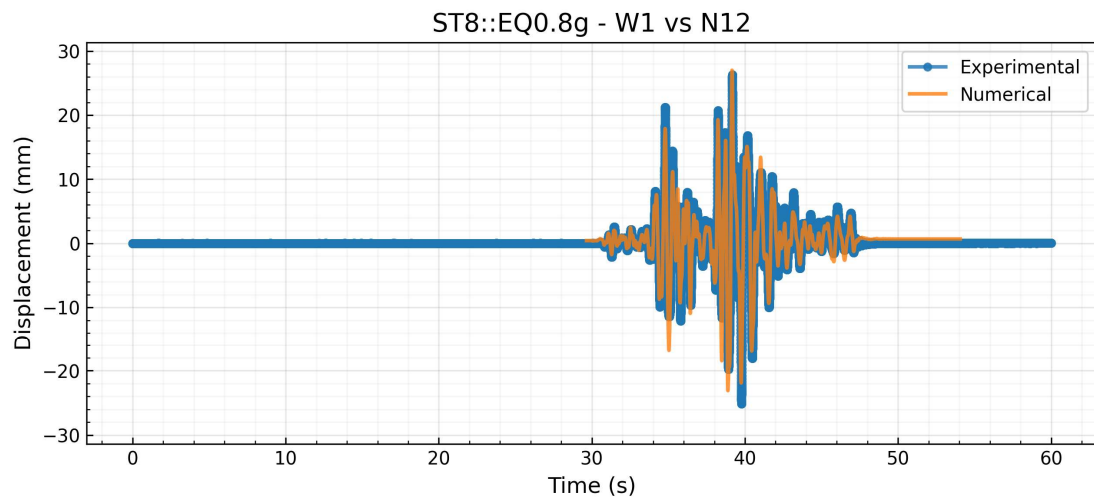


Figure 64 ST8 - Displacement comparison W1 vs N12

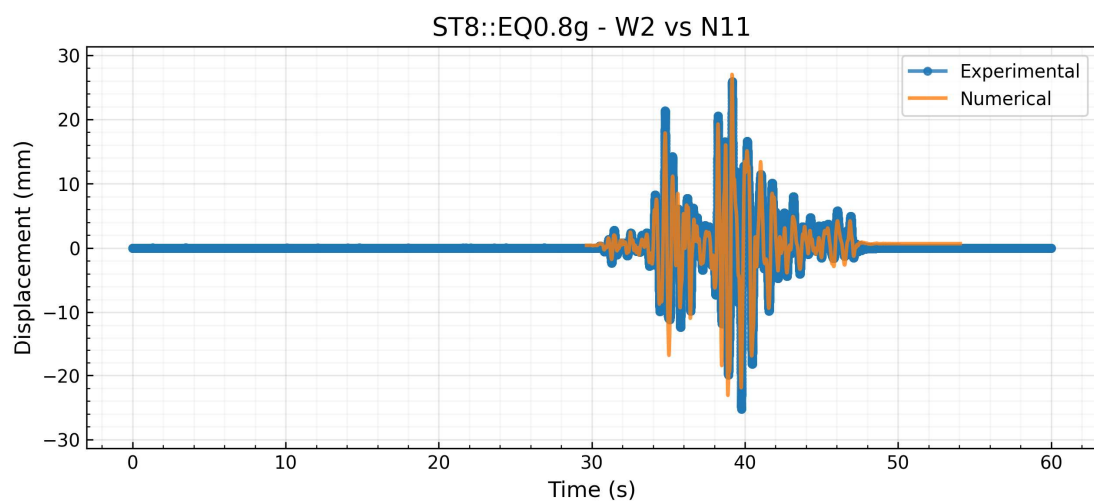


Figure 65 ST8 - Displacement comparison W2 vs N11

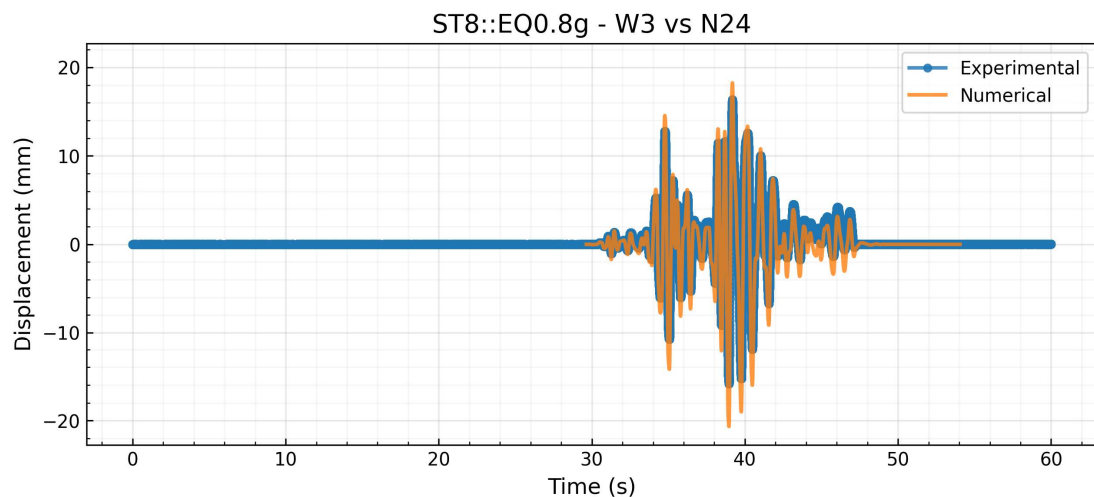


Figure 66 ST8 - Displacement comparison W3 vs N24

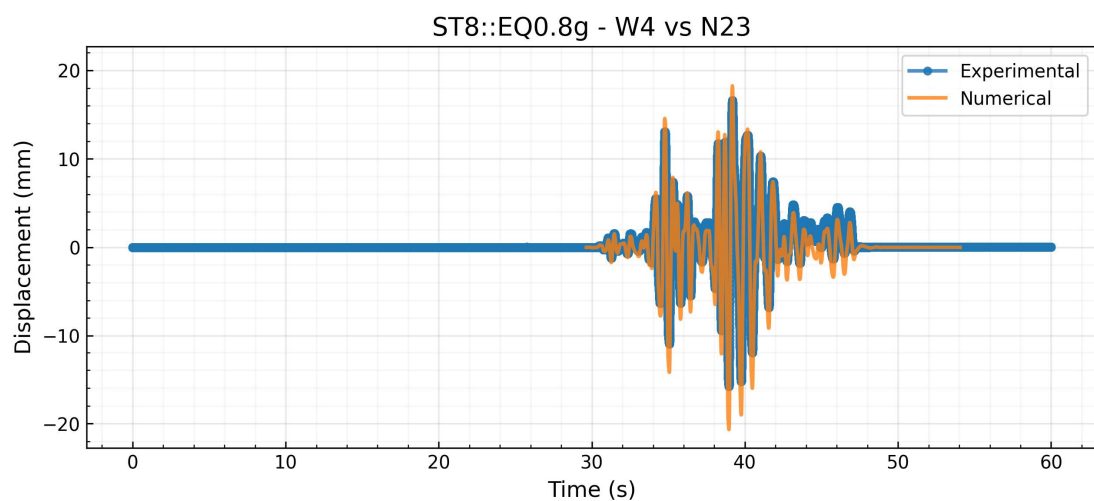


Figure 67 ST8 - Displacement comparison W4 vs N23

4.5 ST10::EQ1.1G RESULTS

The result for draw-wires and accelerometers for ST10::EQ1.1g are presented here.

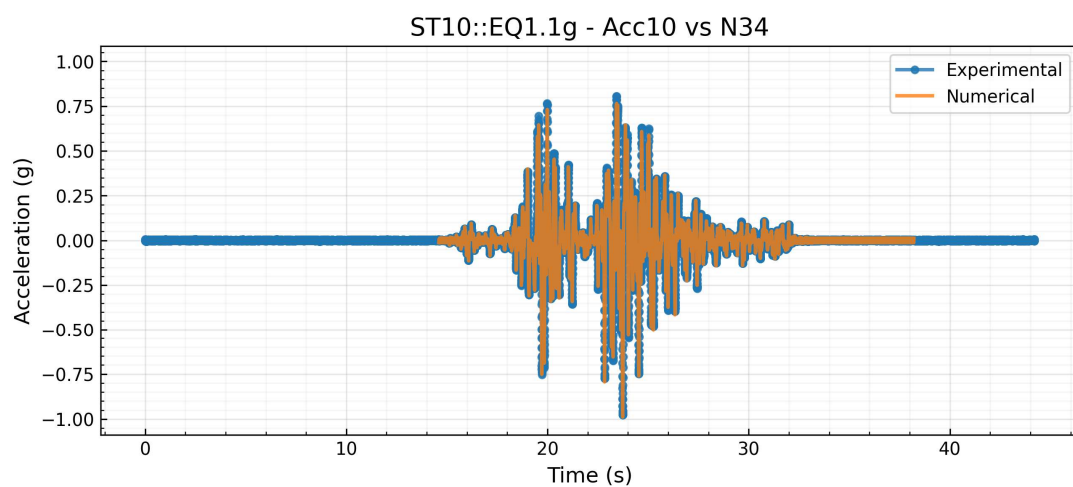


Figure 68 ST10 - Acceleration comparison Acc10 vs N34

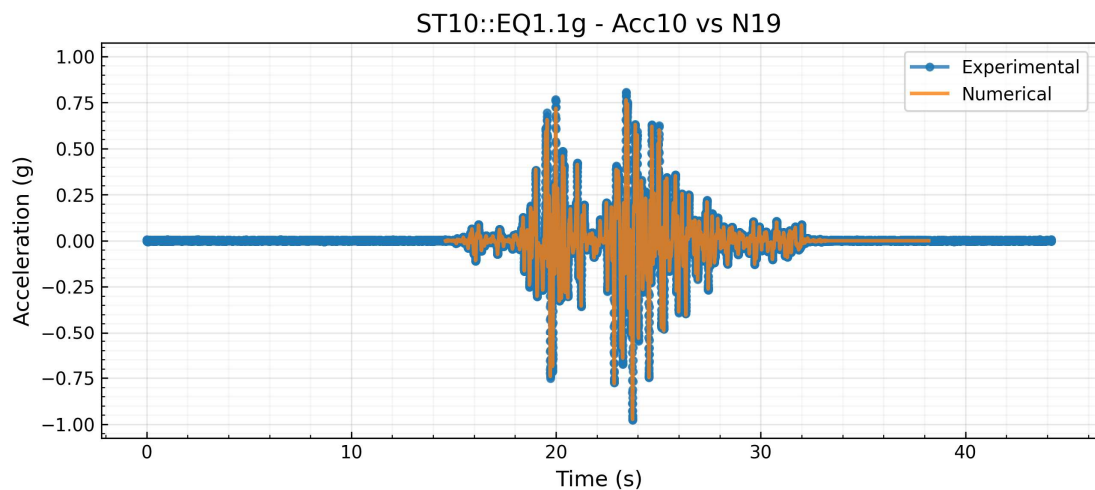


Figure 69 ST10 - Acceleration comparison Acc10 vs N19

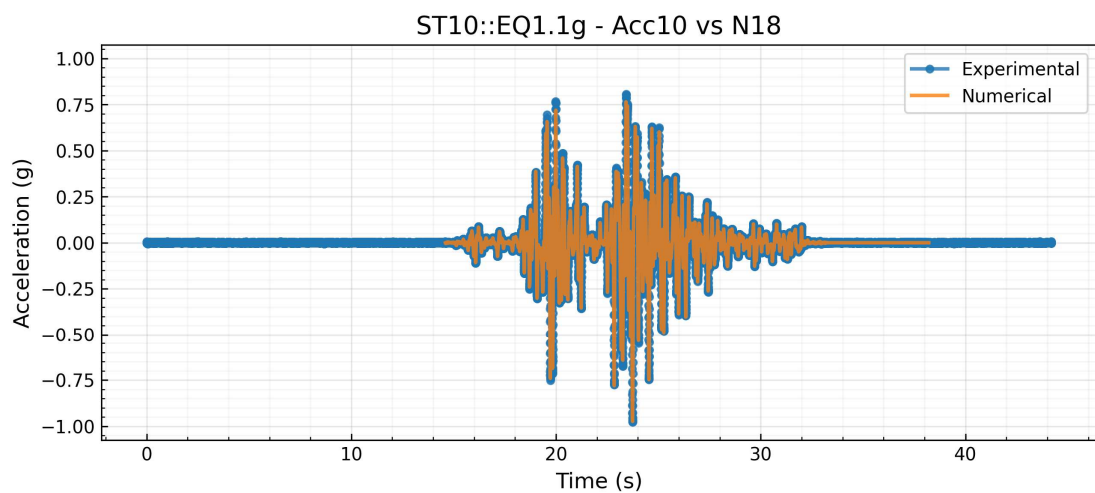


Figure 70 ST10 - Acceleration comparison Acc10 vs N18

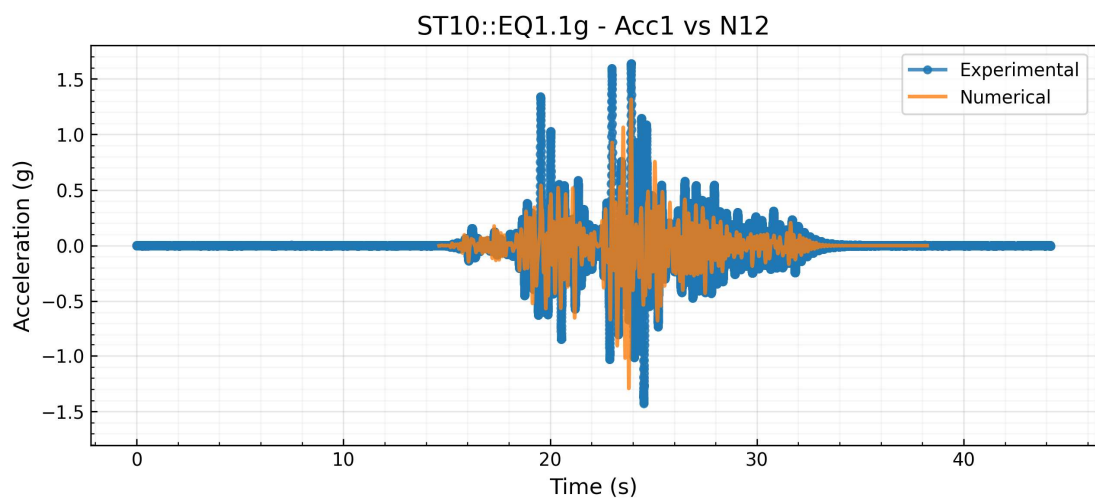


Figure 71 ST10 - Acceleration comparison Acc1 vs N12

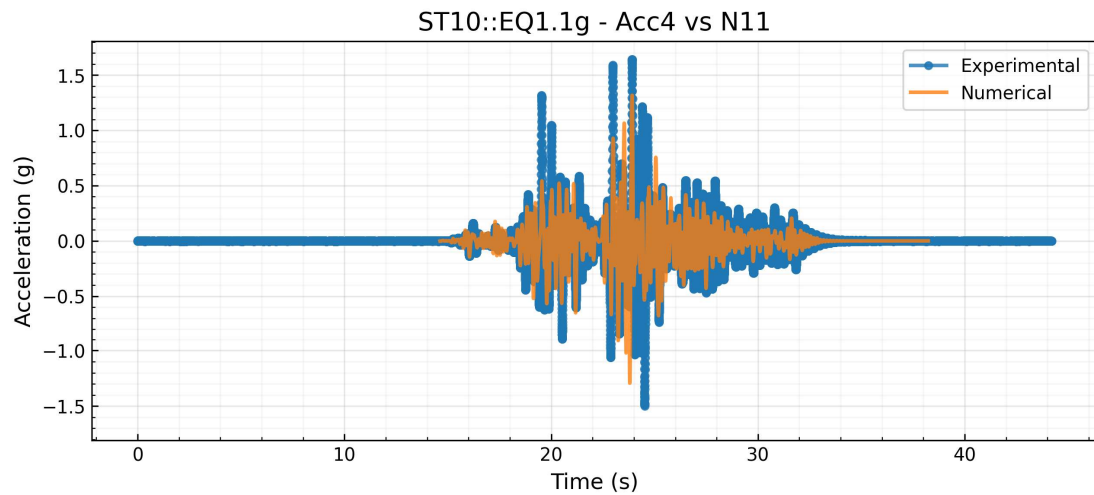


Figure 72 ST10 - Acceleration comparison Acc4 vs N11

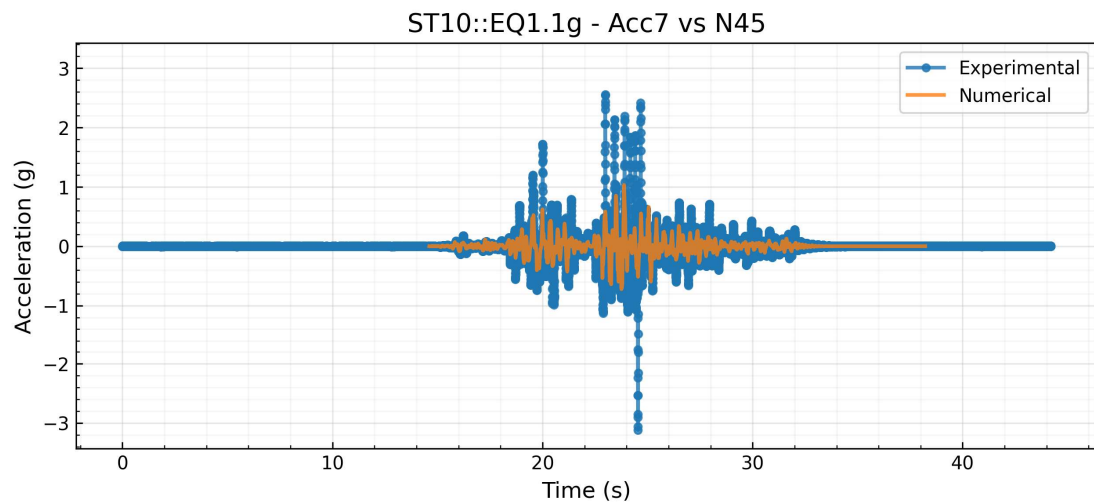


Figure 73 ST10 - Acceleration comparison Acc7 vs N45

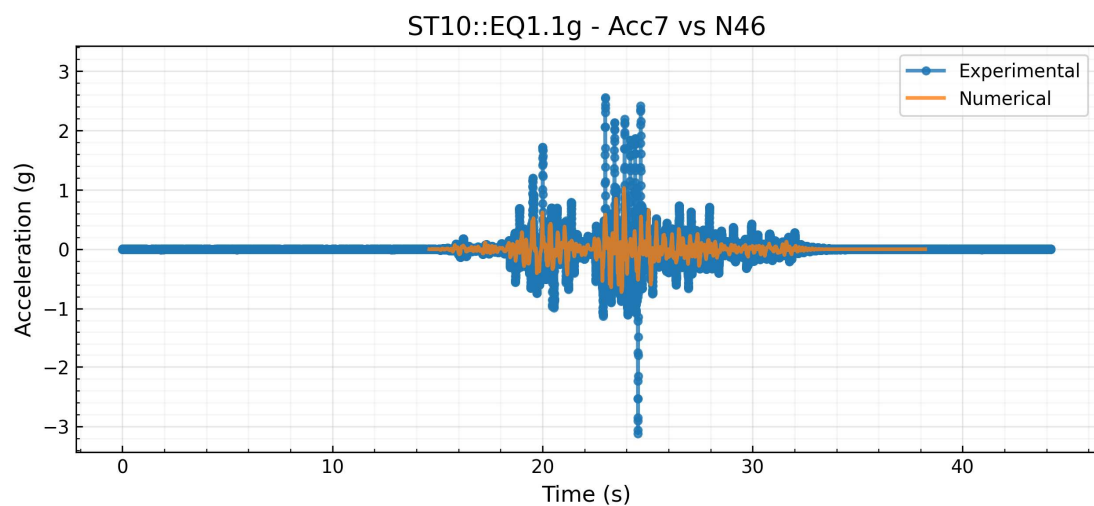


Figure 74 ST10 - Acceleration comparison Acc7 vs N46

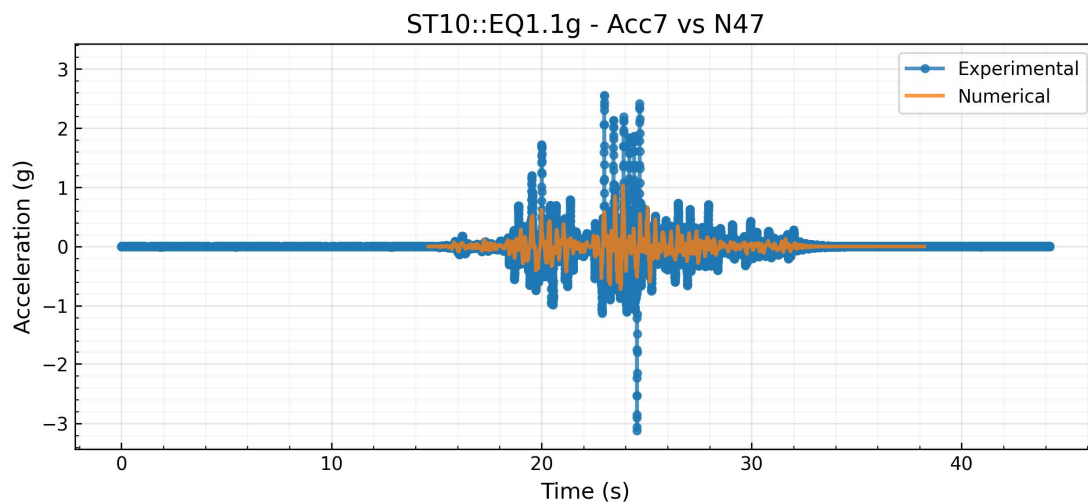


Figure 75 ST10 - Acceleration comparison Acc7 vs N47

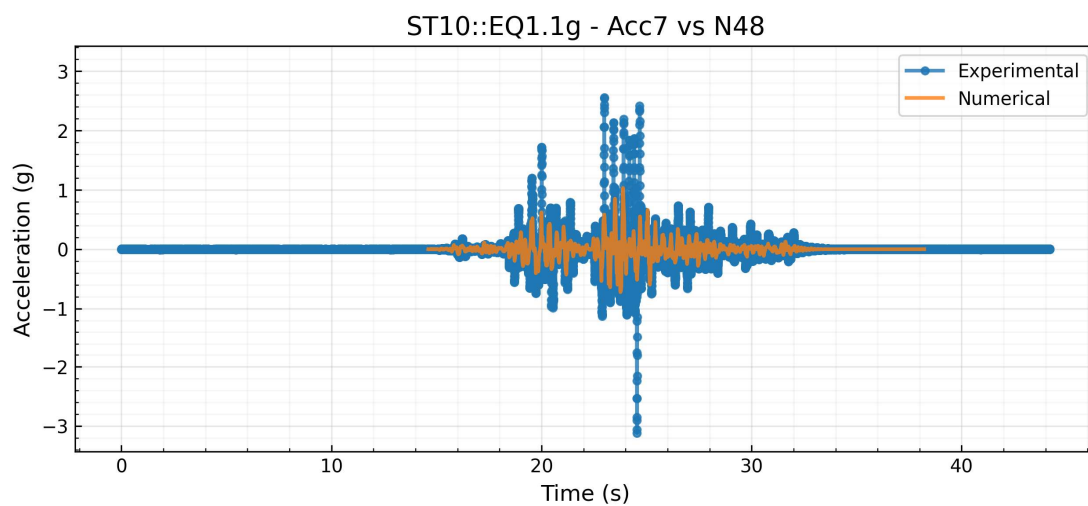


Figure 76 ST10 - Acceleration comparison Acc7 vs N48

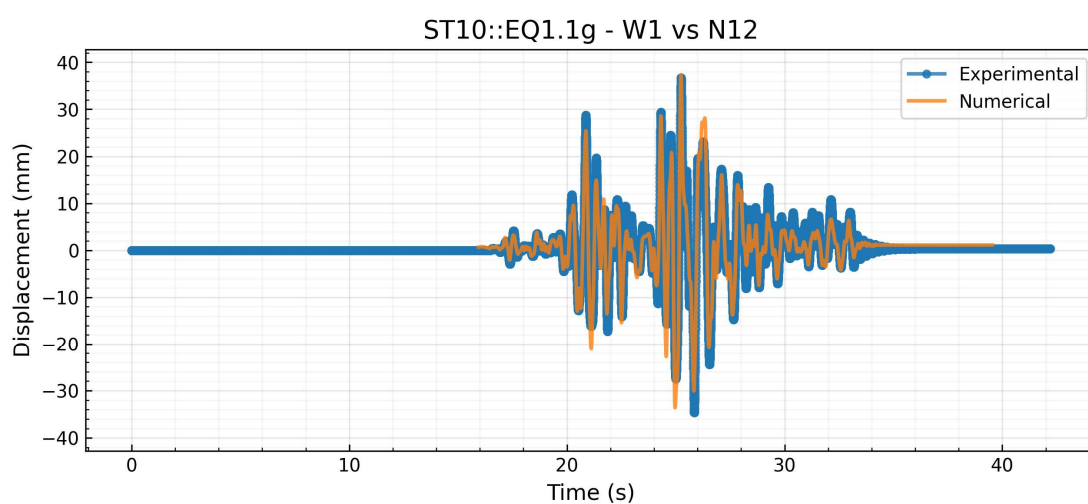


Figure 77 ST10 - Displacement comparison W1 vs N12

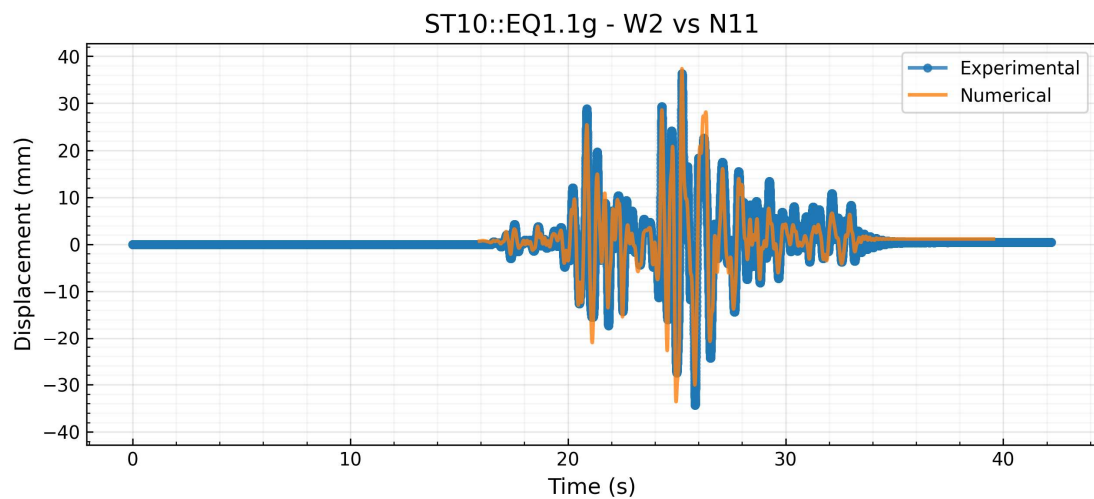


Figure 78 ST10 - Displacement comparison W2 vs N11

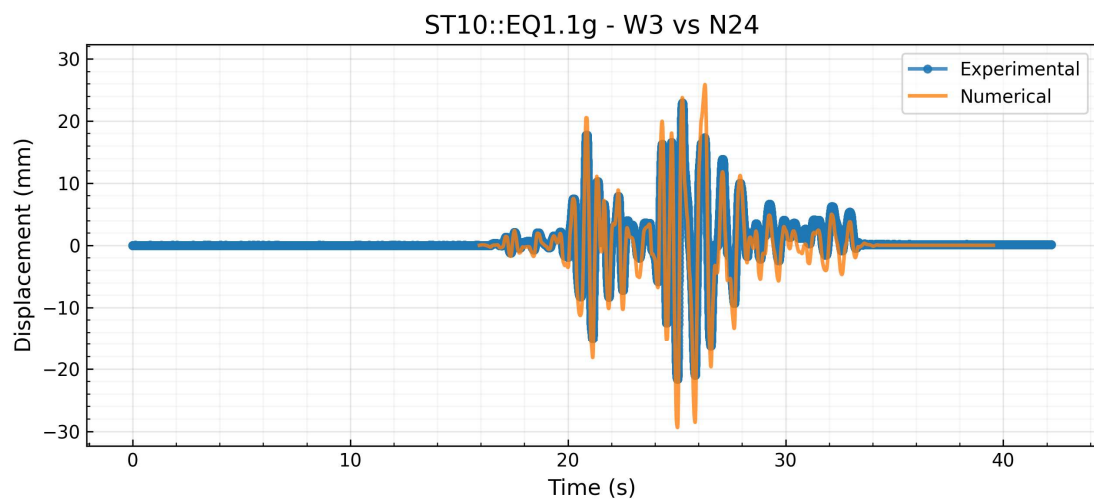


Figure 79 ST10 - Displacement comparison W3 vs N24

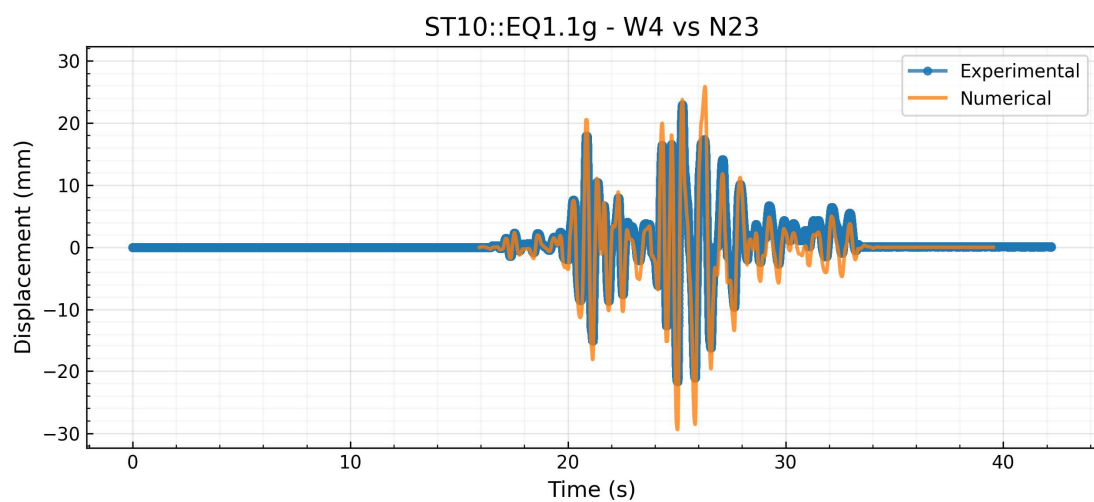


Figure 80 ST10 - Displacement comparison W4 vs N23

4.6 ST1::WNB0.1G RESULTS

The result for draw-wires and accelerometers for ST1::WNB0.1g are presented here.

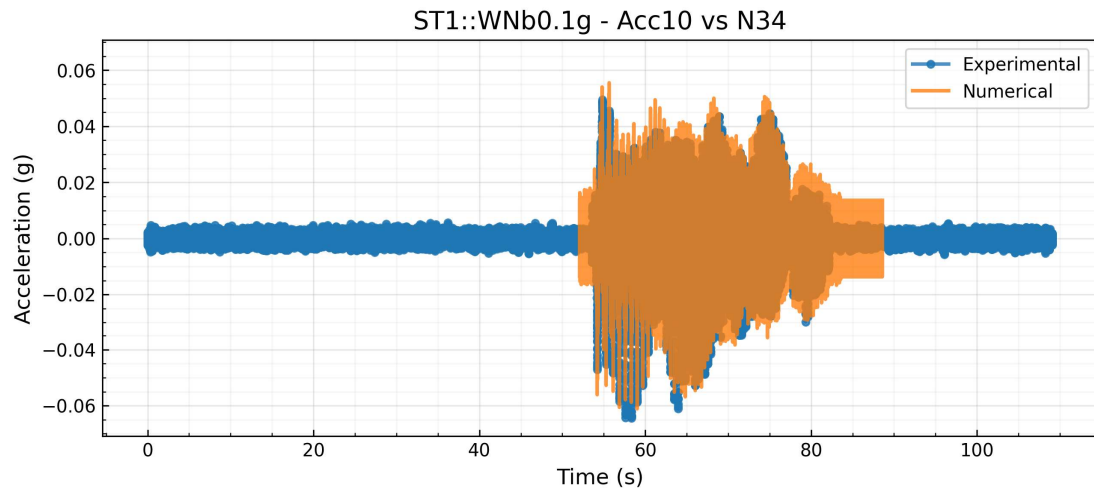


Figure 81 ST1 - Acceleration comparison Acc10 vs N34

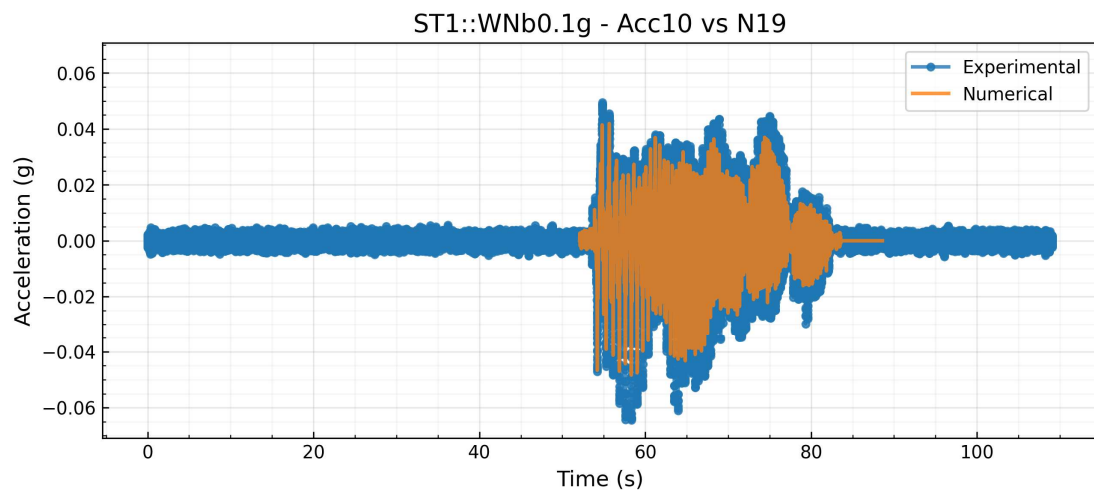


Figure 82 ST1 - Acceleration comparison Acc10 vs N19

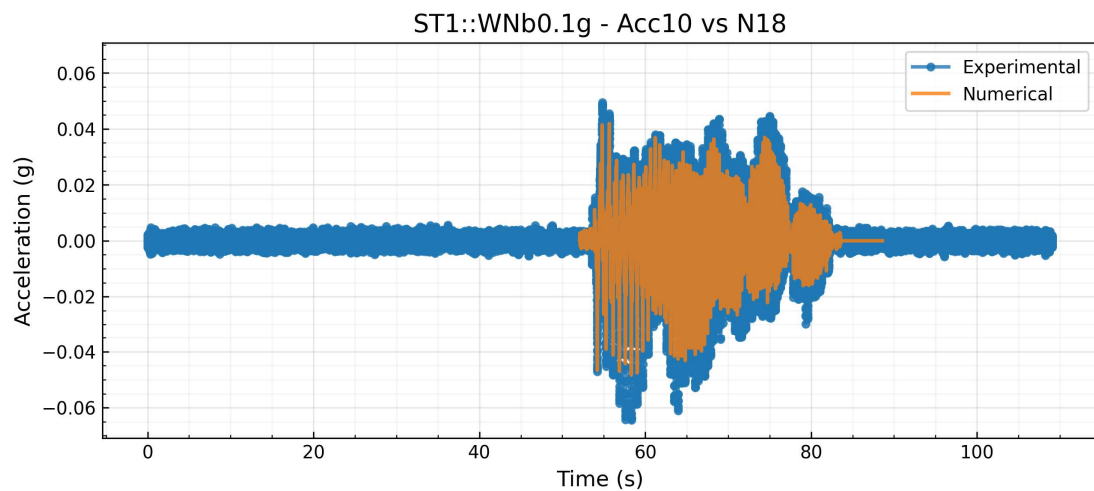
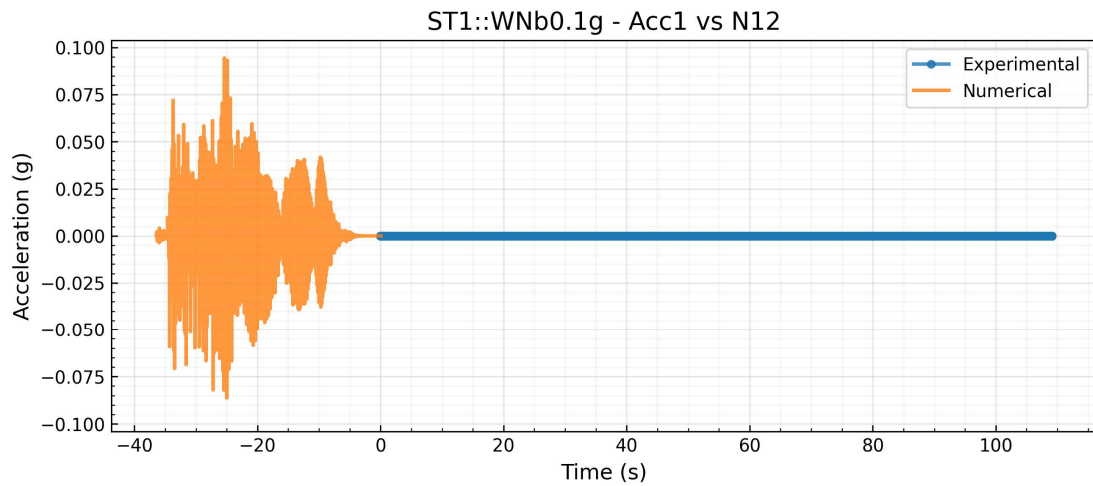


Figure 83 ST1 - Acceleration comparison Acc10 vs N18



Acc1 Record Not Available

Figure 84 ST1 - Acceleration comparison Acc1 vs N12

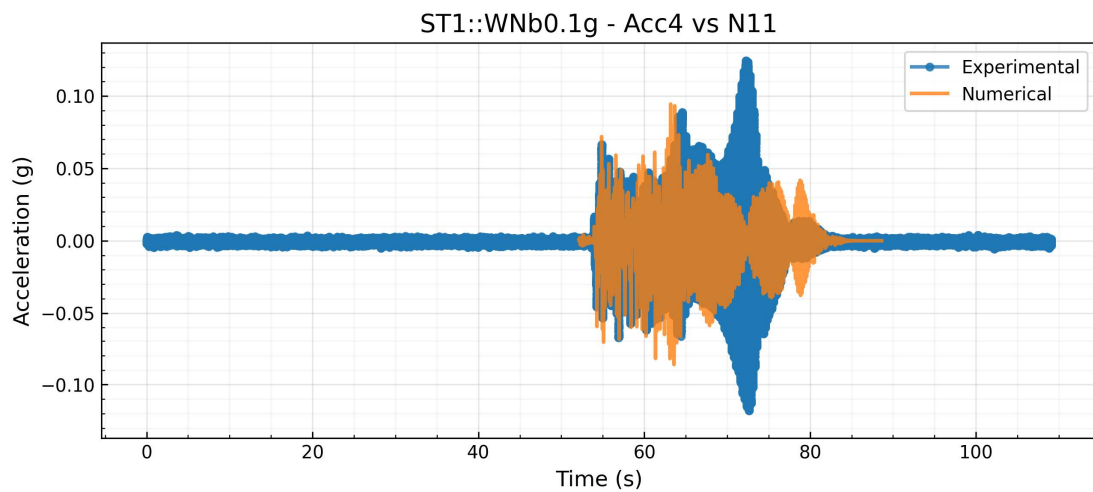


Figure 85 ST1 - Acceleration comparison Acc4 vs N11

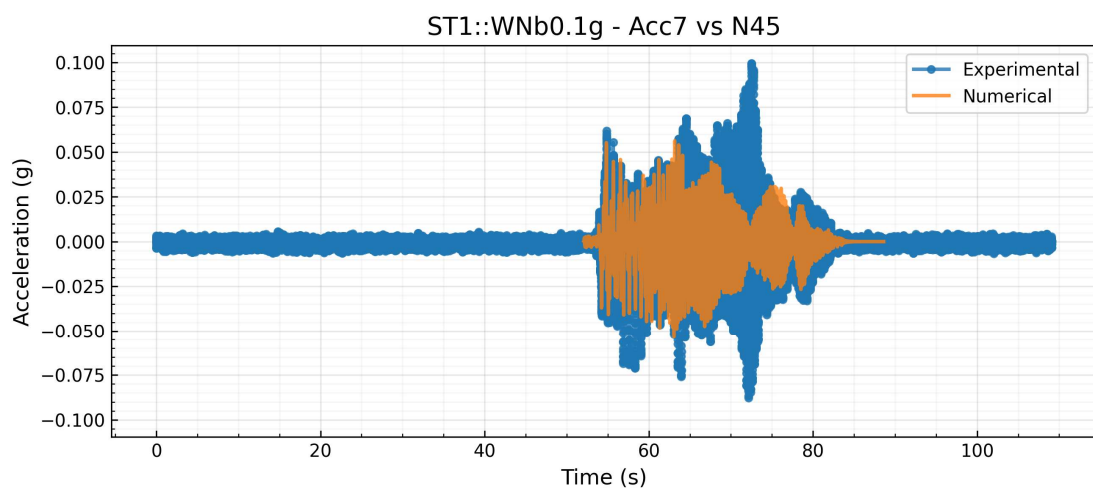


Figure 86 ST1 - Acceleration comparison Acc7 vs N45

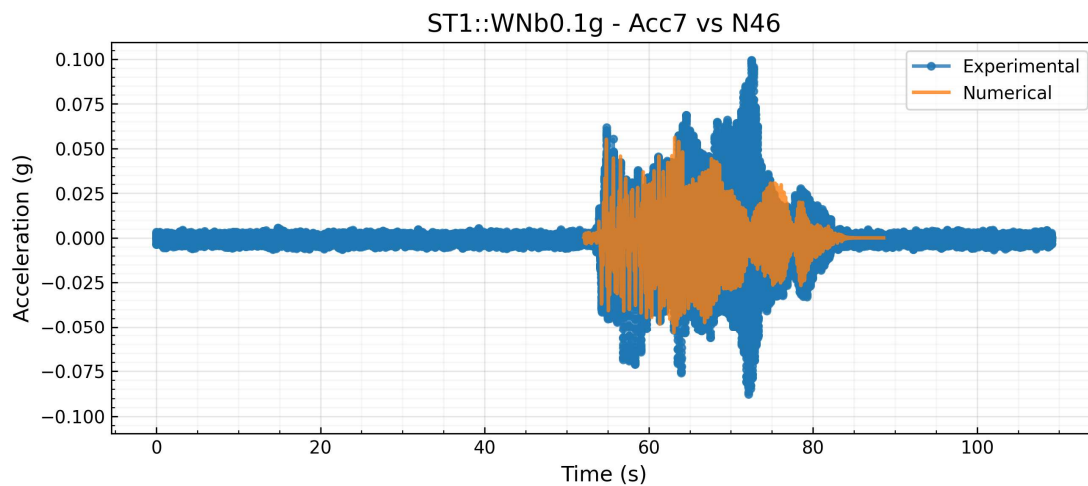


Figure 87 ST1 - Acceleration comparison Acc7 vs N46

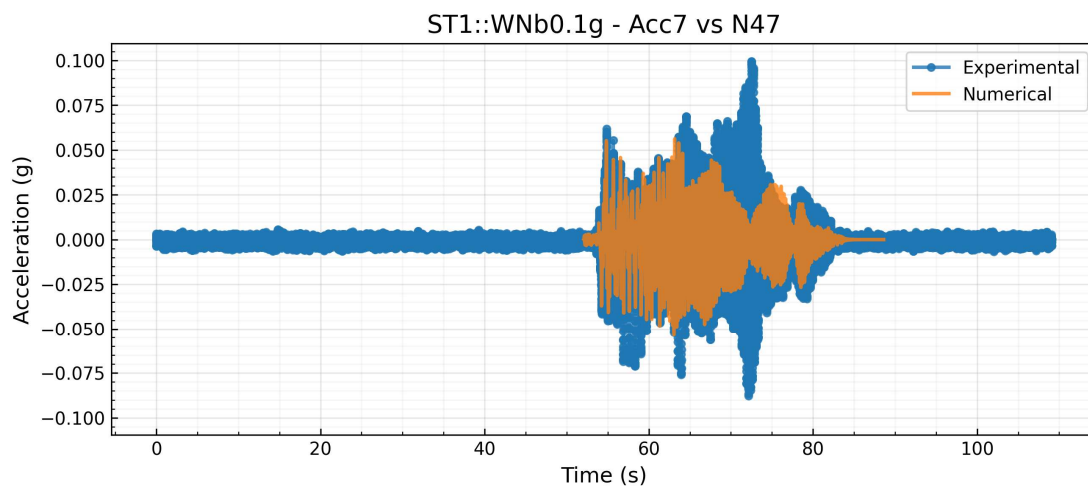


Figure 88 ST1 - Acceleration comparison Acc7 vs N47

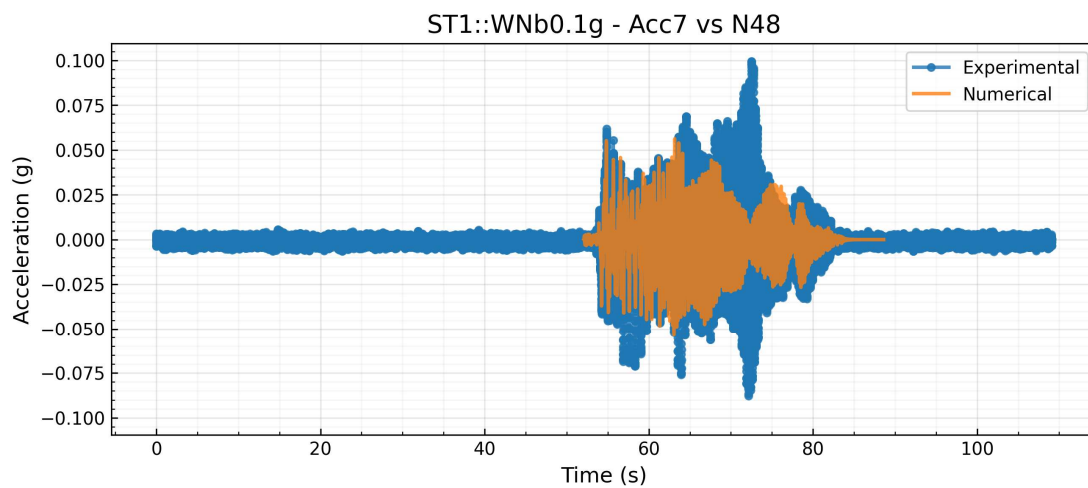


Figure 89 ST1 - Acceleration comparison Acc7 vs N48

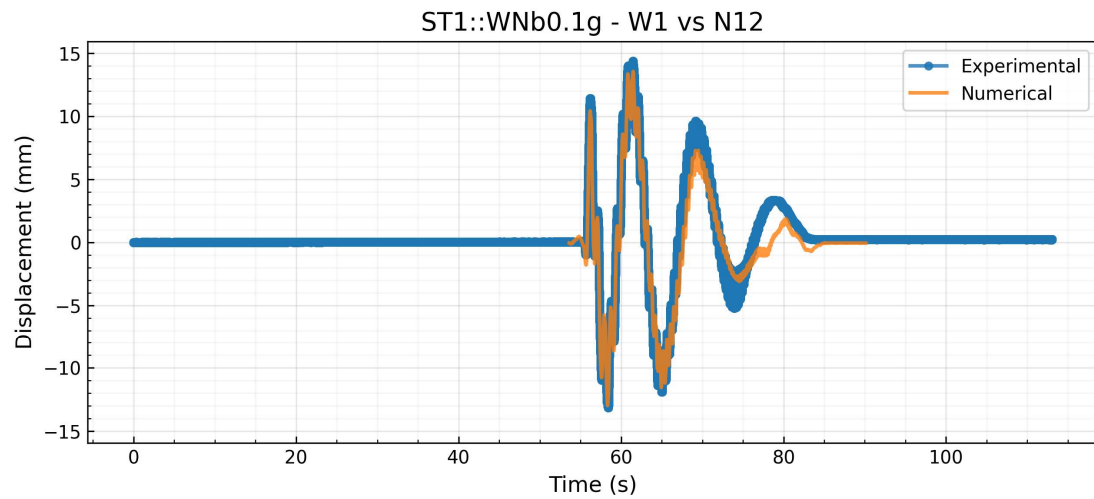


Figure 90 ST1 - Displacement comparison W1 vs N12

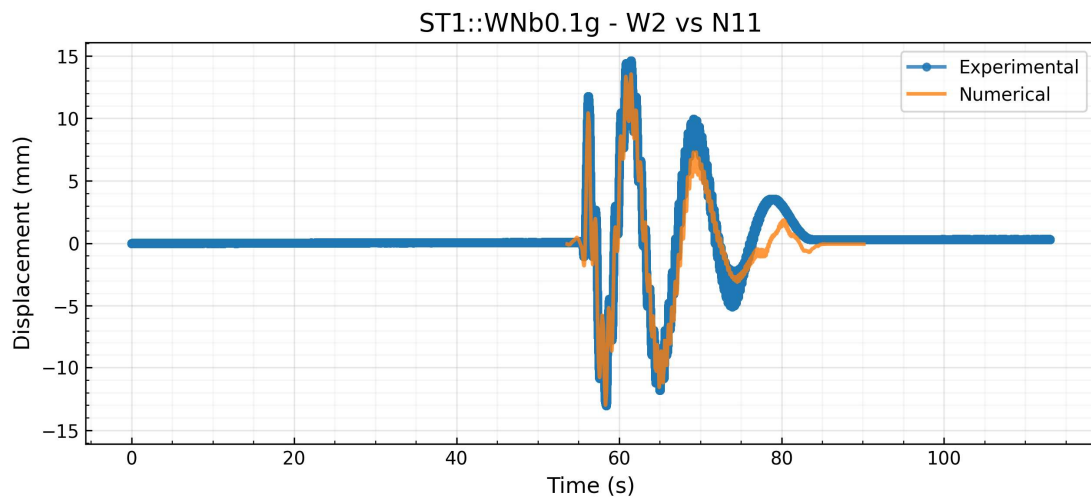


Figure 91 ST1 - Displacement comparison W2 vs N11

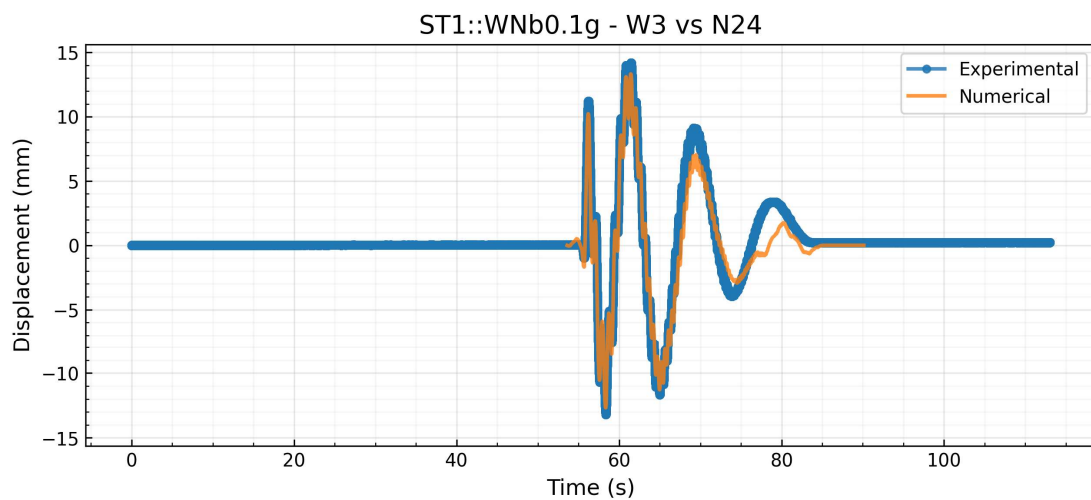


Figure 92 ST1 - Displacement comparison W3 vs N24

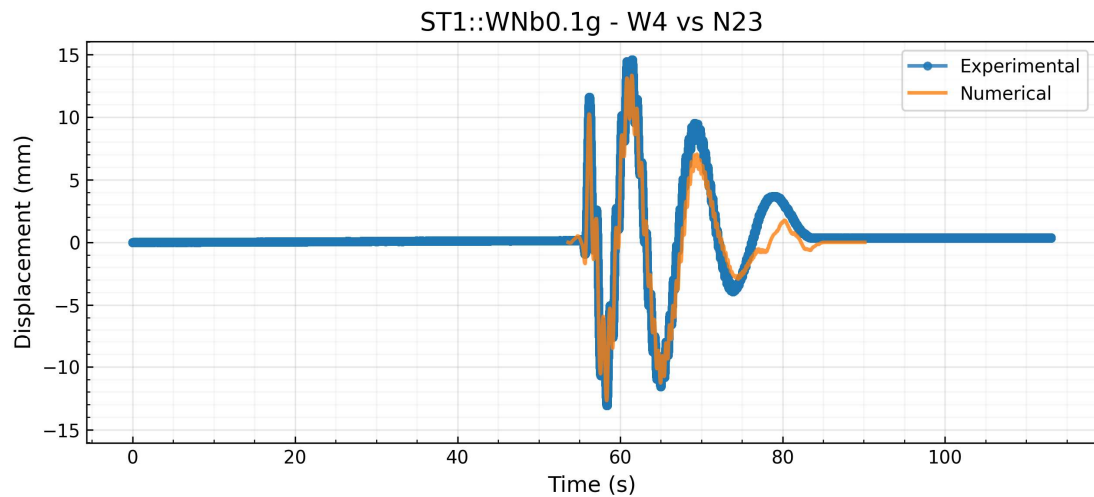


Figure 93 ST1 - Displacement comparison W4 vs N23

4.7 ST3::WNB0.2G RESULTS

The result for draw-wires and accelerometers for ST3::WNB0.2g are presented here.

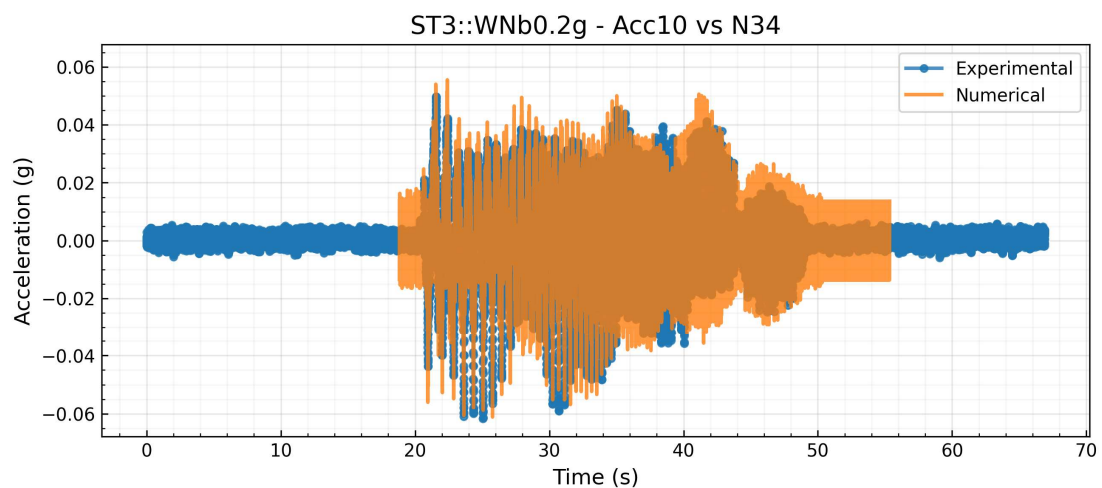


Figure 94 ST3 - Acceleration comparison Acc10 vs N34

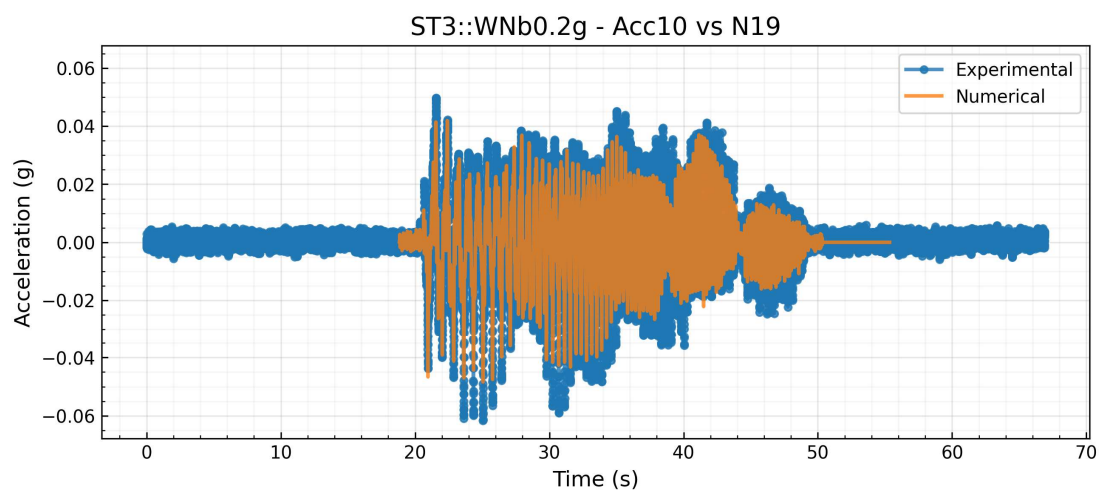


Figure 95 ST3 - Acceleration comparison Acc10 vs N19

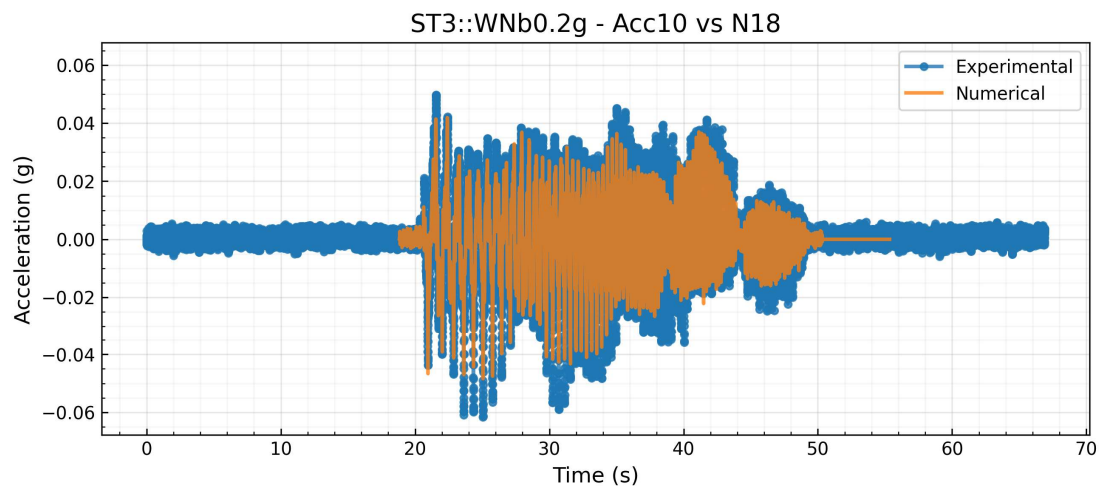


Figure 96 ST3 - Acceleration comparison Acc10 vs N18

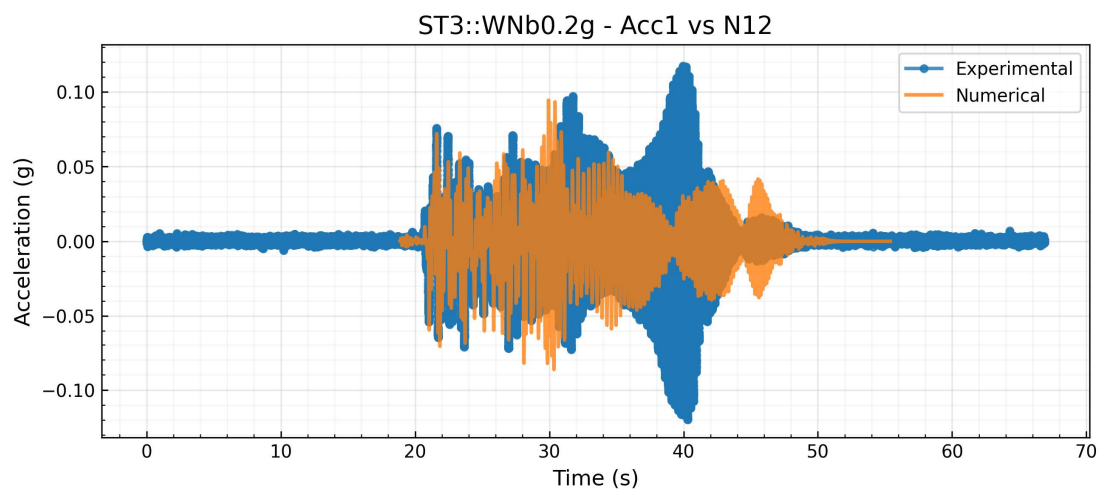


Figure 97 ST3 - Acceleration comparison Acc1 vs N12

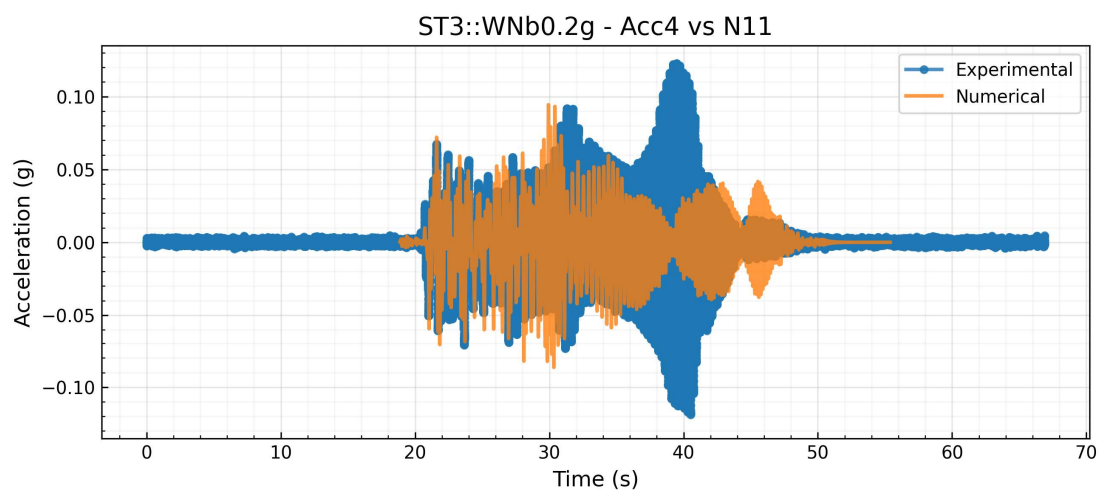


Figure 98 ST3 - Acceleration comparison Acc4 vs N11

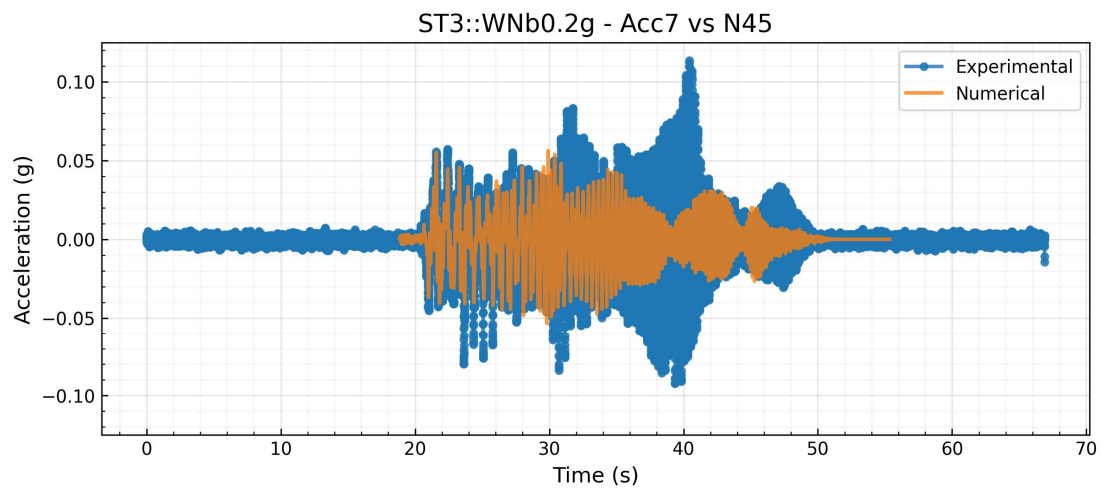


Figure 99 ST3 - Acceleration comparison Acc7 vs N45

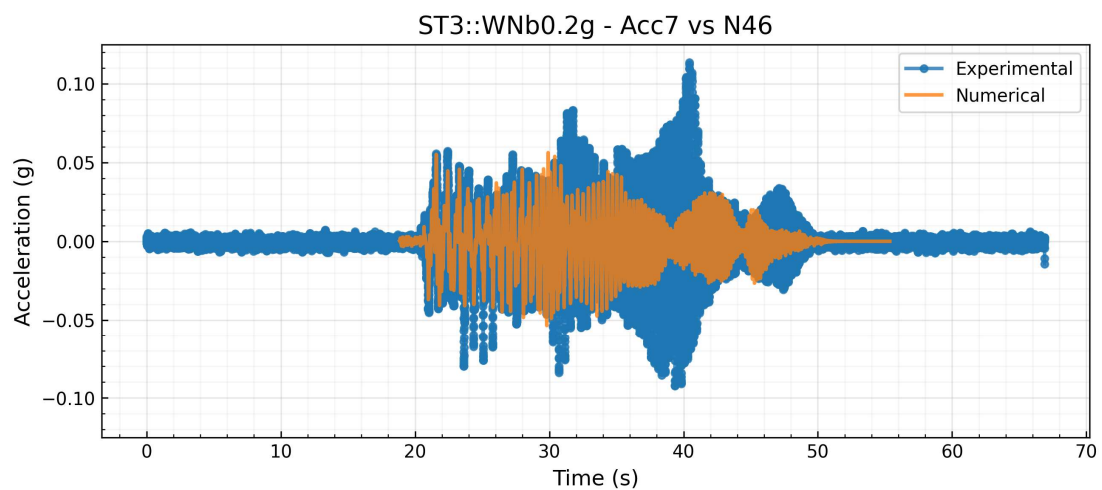


Figure 100 ST3 - Acceleration comparison Acc7 vs N46

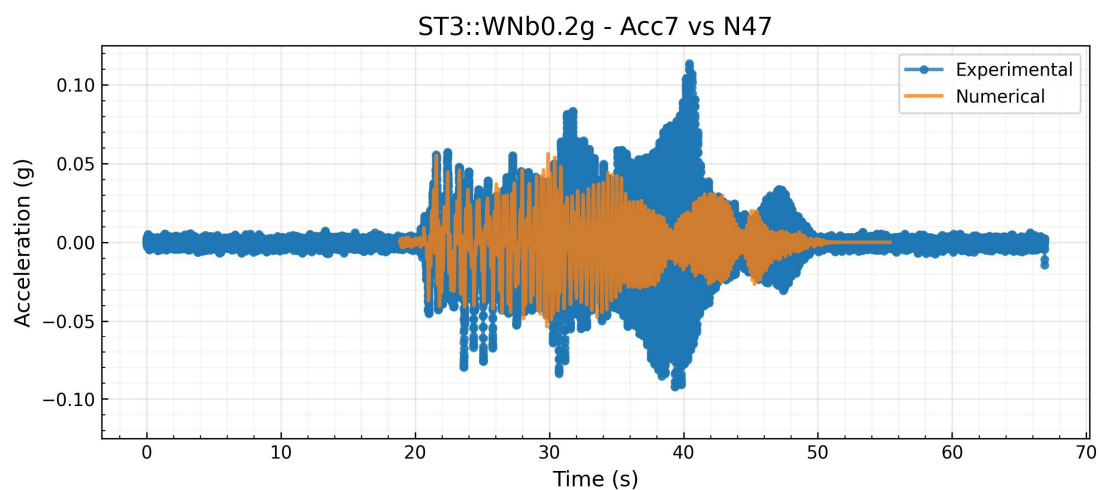


Figure 101 ST3 - Acceleration comparison Acc7 vs N47

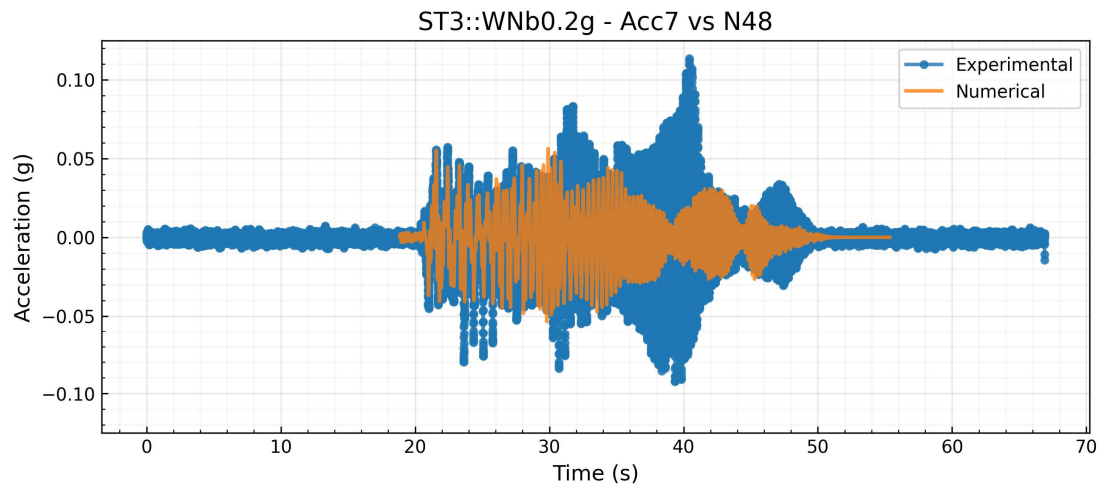


Figure 102 ST3 - Acceleration comparison Acc7 vs N48

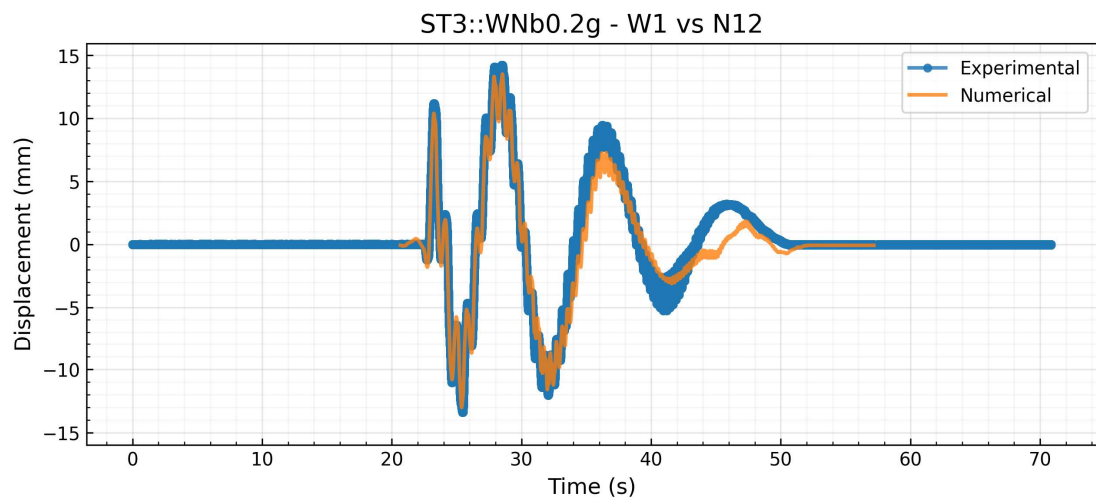


Figure 103 ST3 - Displacement comparison W1 vs N12

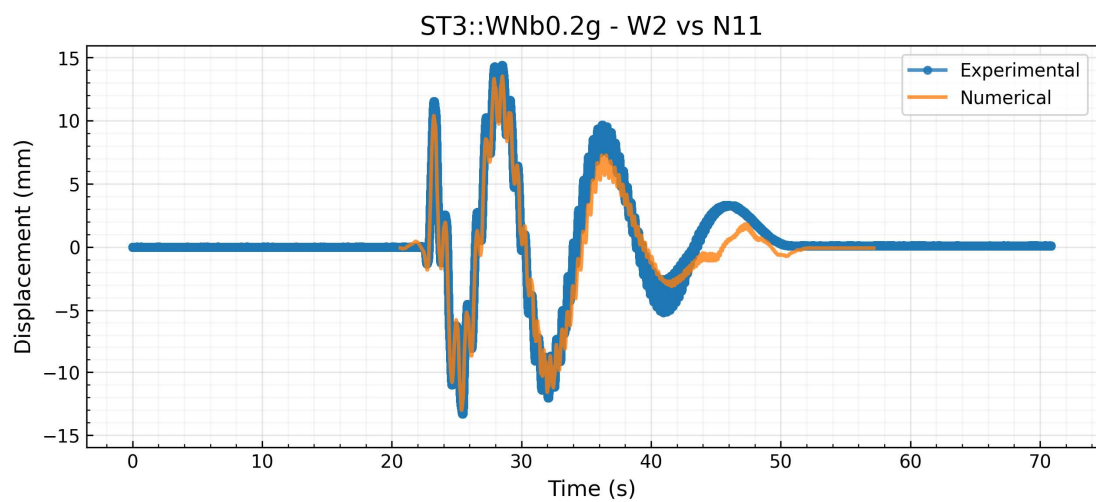


Figure 104 ST3 - Displacement comparison W2 vs N11

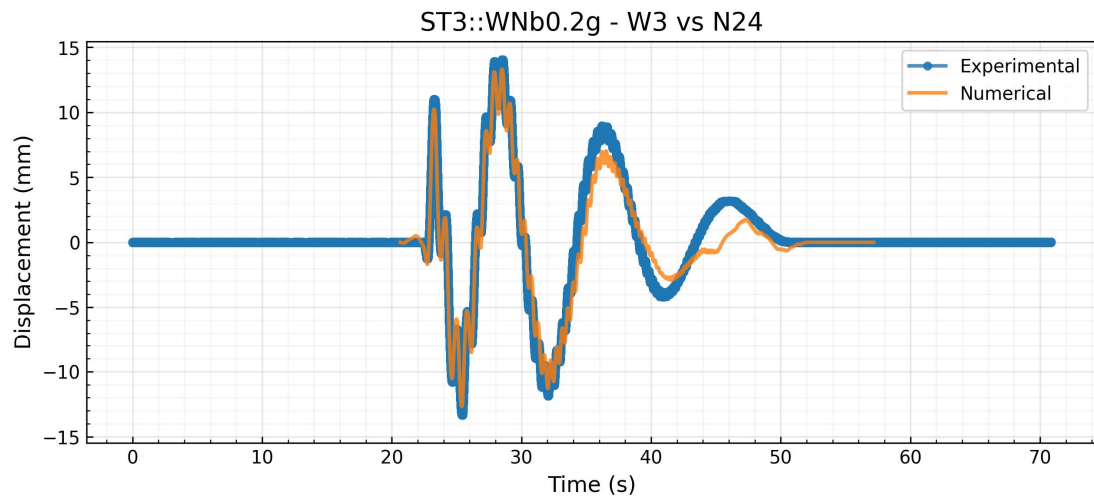


Figure 105 ST3 - Displacement comparison W3 vs N24

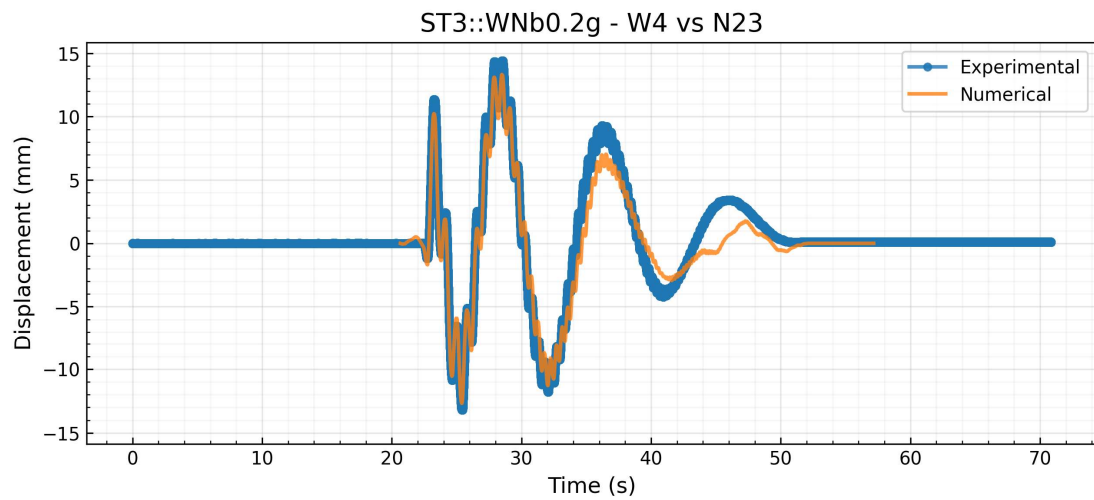


Figure 106 ST3 - Displacement comparison W4 vs N23

4.8 ST5::WNB0.5G RESULTS

The result for draw-wires and accelerometers for ST5::WNb0.5g are presented here.

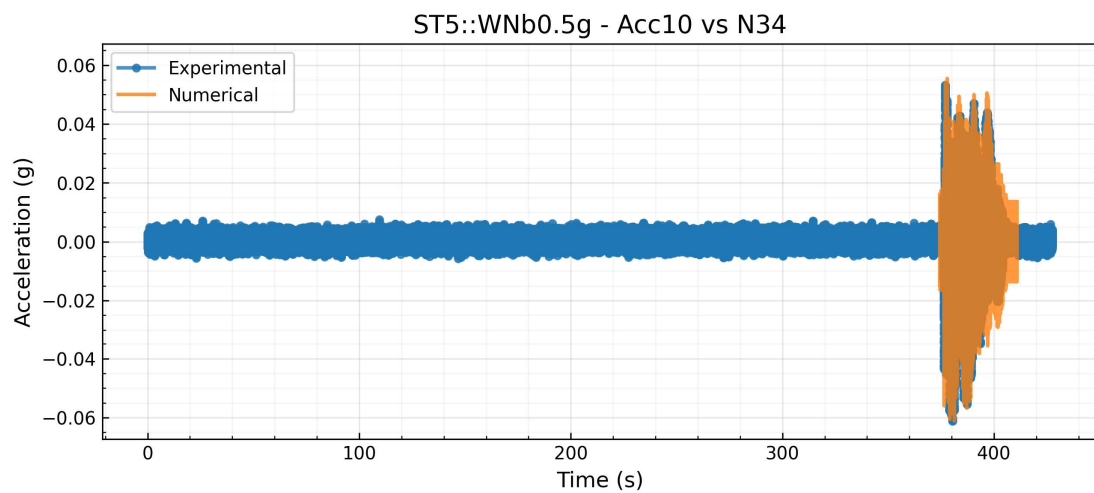


Figure 107 ST5 - Acceleration comparison Acc10 vs N34

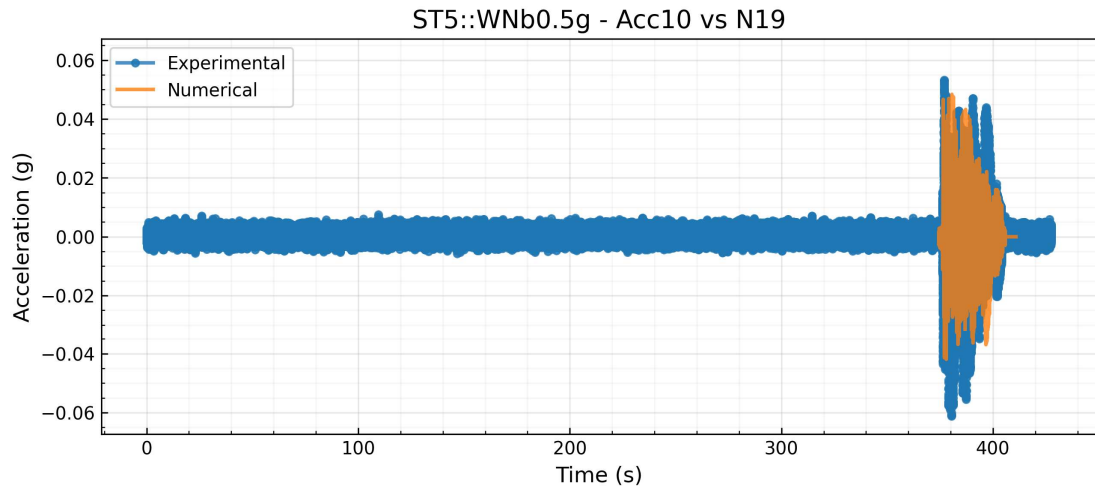


Figure 108 ST5 - Acceleration comparison Acc10 vs N19

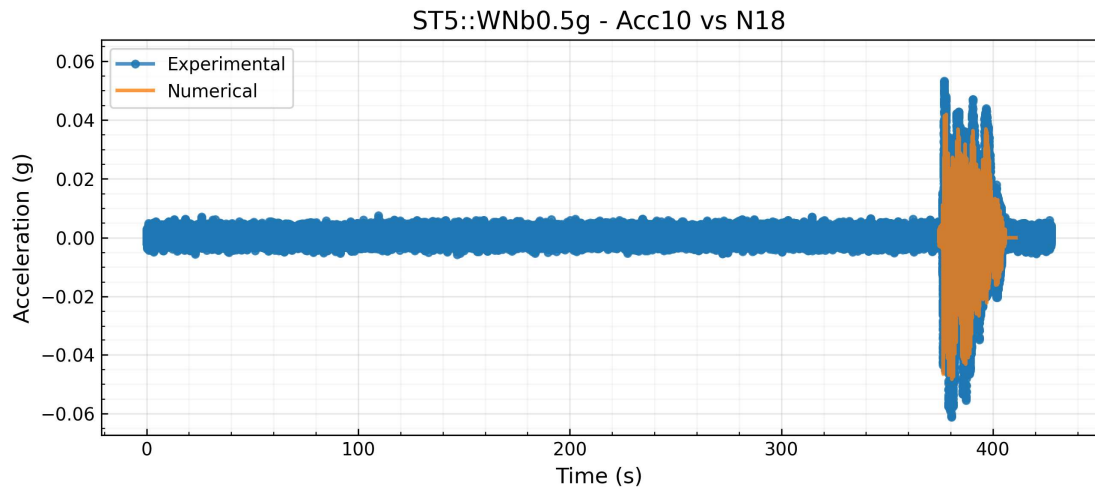


Figure 109 ST5 - Acceleration comparison Acc10 vs N18

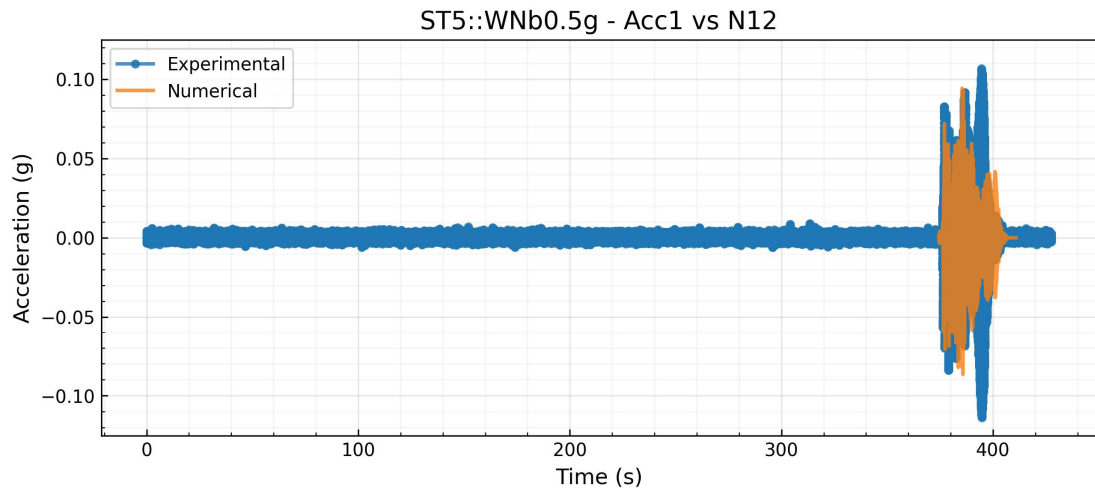


Figure 110 ST5 - Acceleration comparison Acc1 vs N12

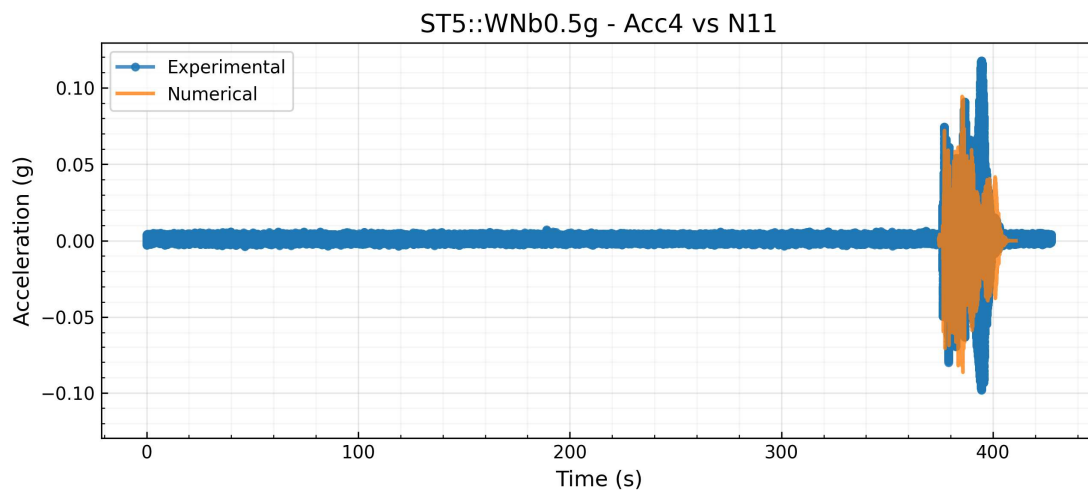


Figure 111 ST5 - Acceleration comparison Acc4 vs N11

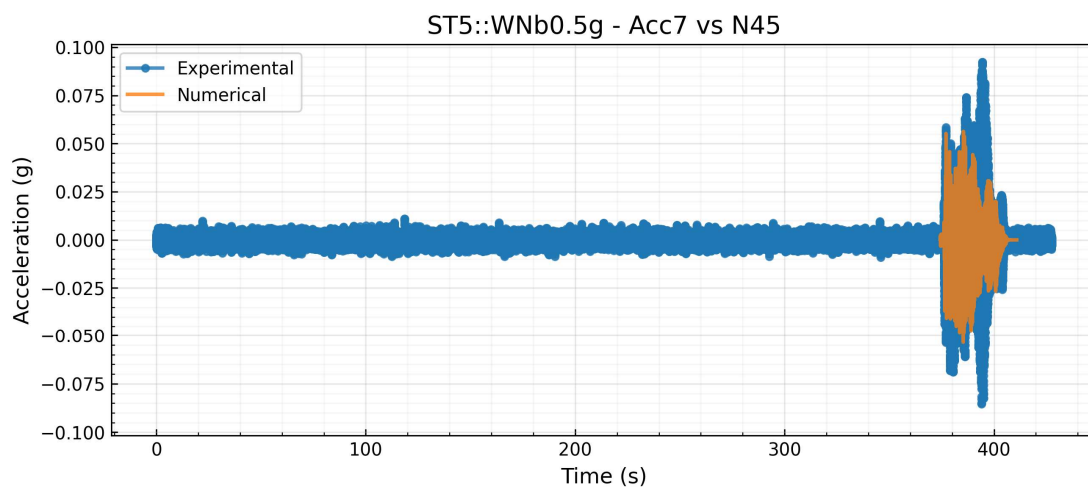


Figure 112 ST5 - Acceleration comparison Acc7 vs N45

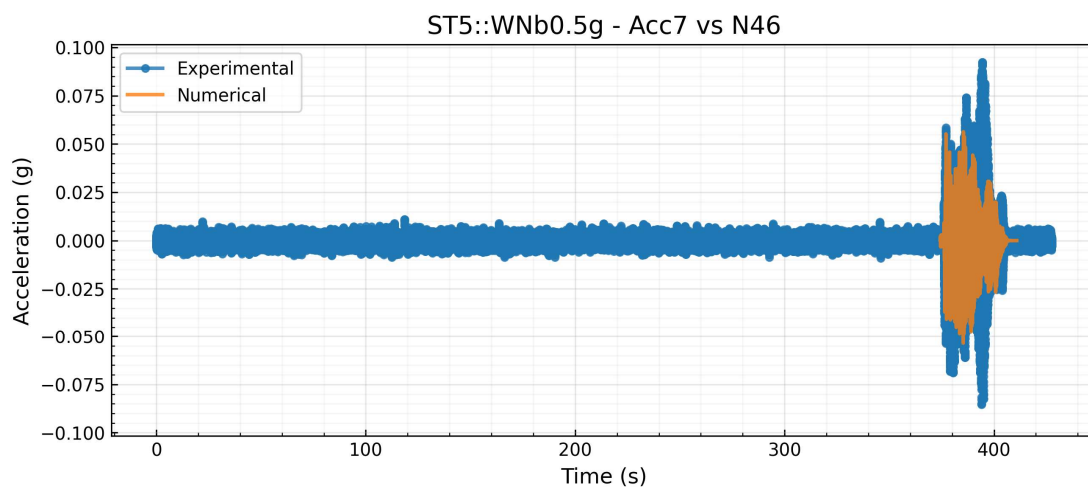


Figure 113 ST5 - Acceleration comparison Acc7 vs N46

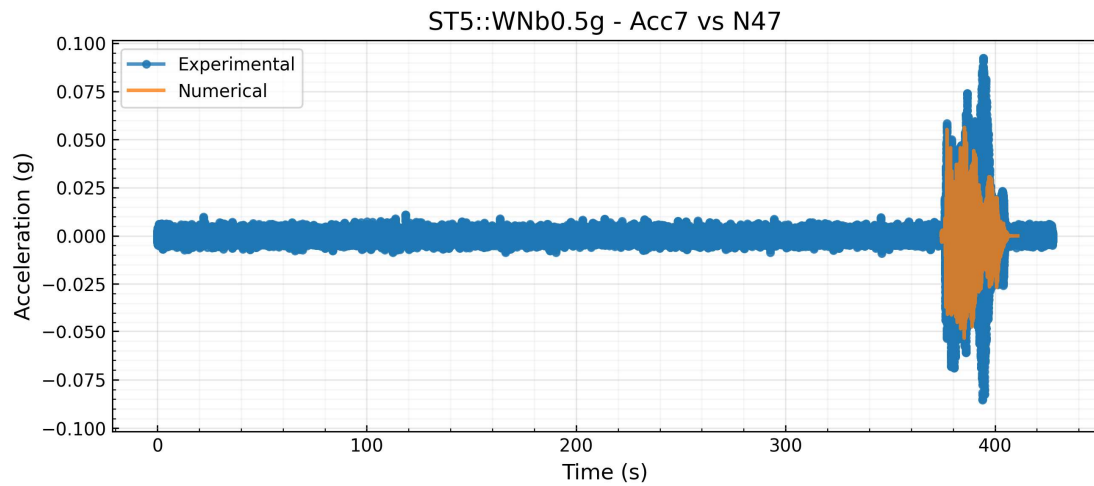


Figure 114 ST5 - Acceleration comparison Acc7 vs N47

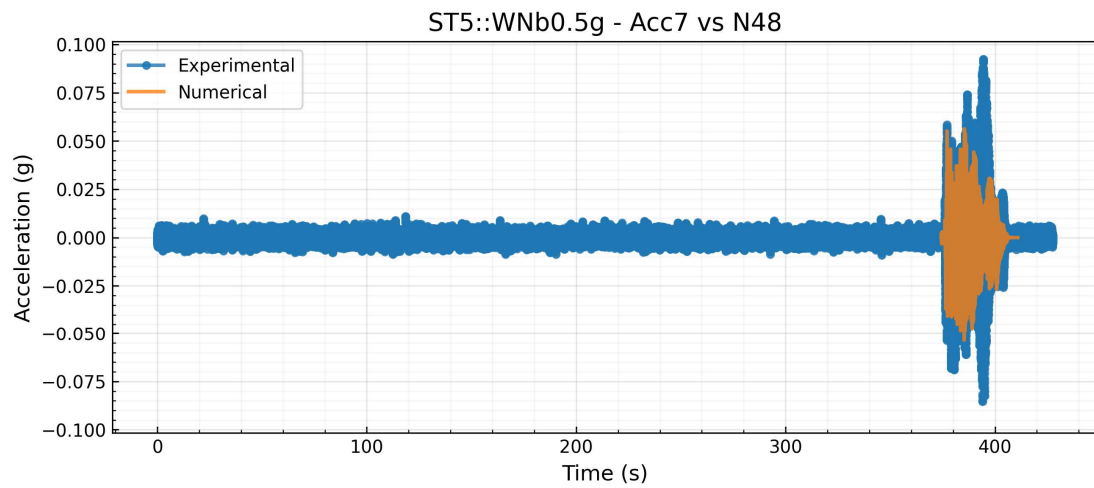


Figure 115 ST5 - Acceleration comparison Acc7 vs N48

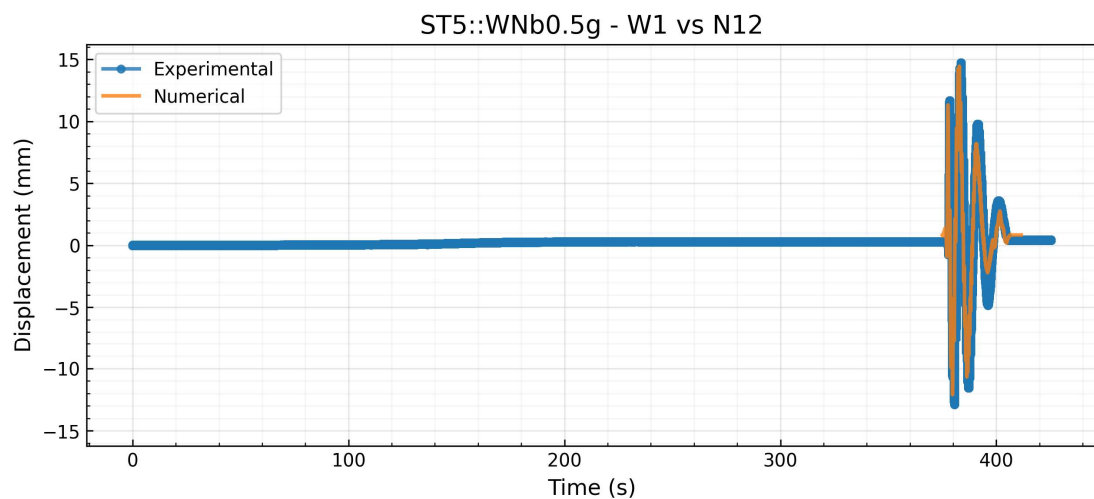


Figure 116 ST5 - Displacement comparison W1 vs N12

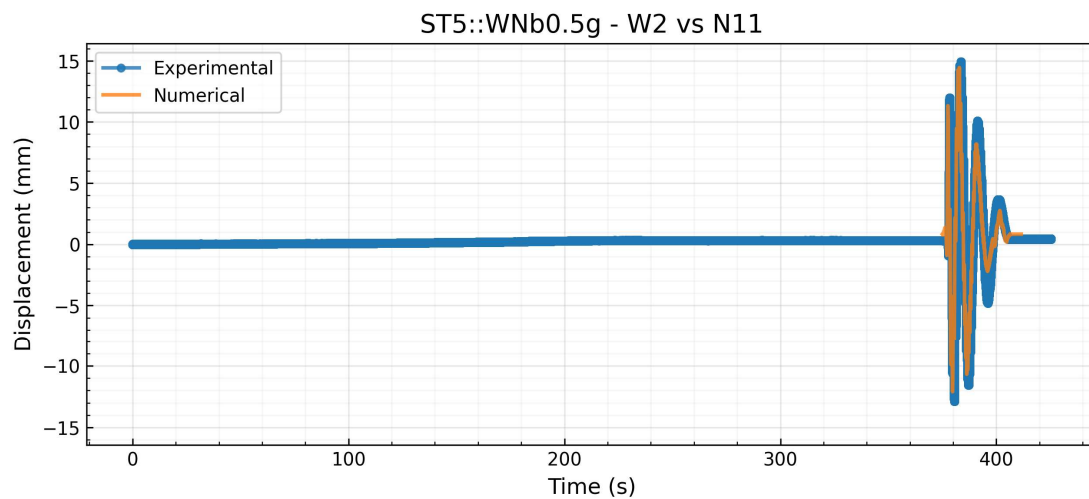


Figure 117 ST5 - Displacement comparison W2 vs N11

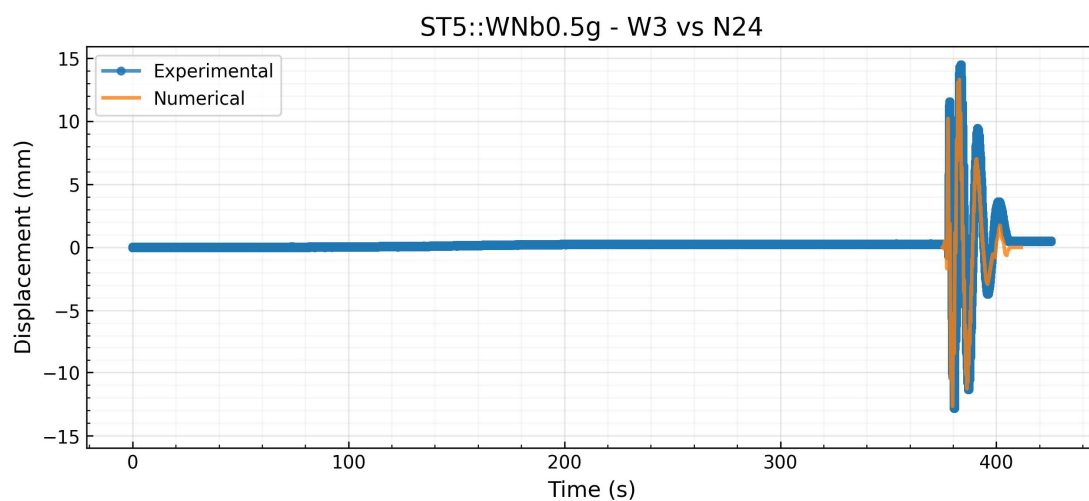


Figure 118 ST5 - Displacement comparison W3 vs N24

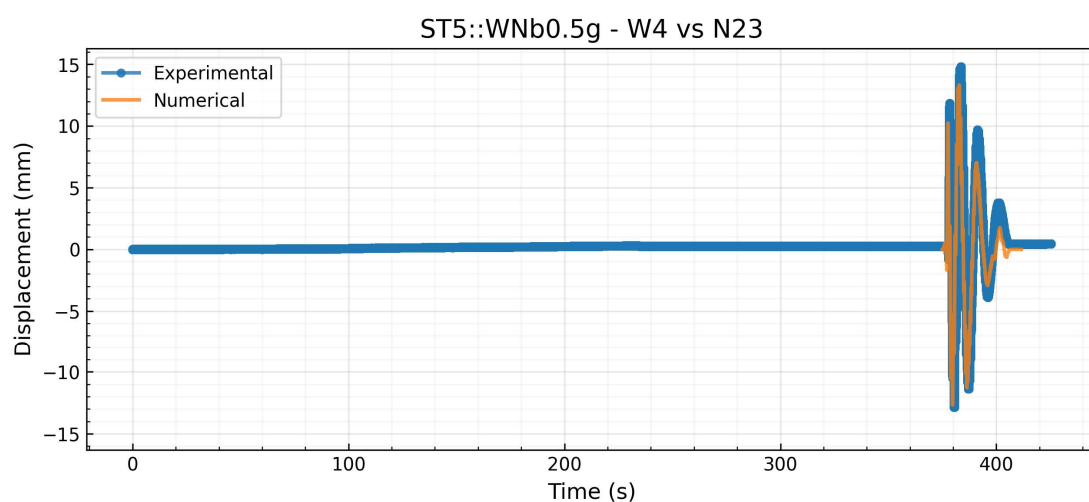


Figure 119 ST5 - Displacement comparison W4 vs N23

4.9 ST7::WNB0.8G RESULTS

The result for draw-wires and accelerometers for ST7::WNB0.8g are presented here.

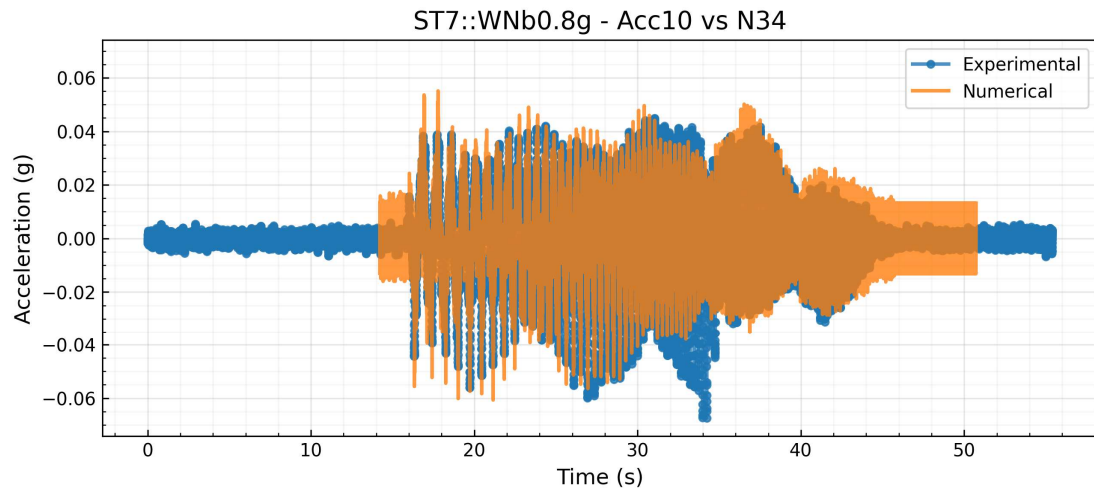


Figure 120 ST7 - Acceleration comparison Acc10 vs N34

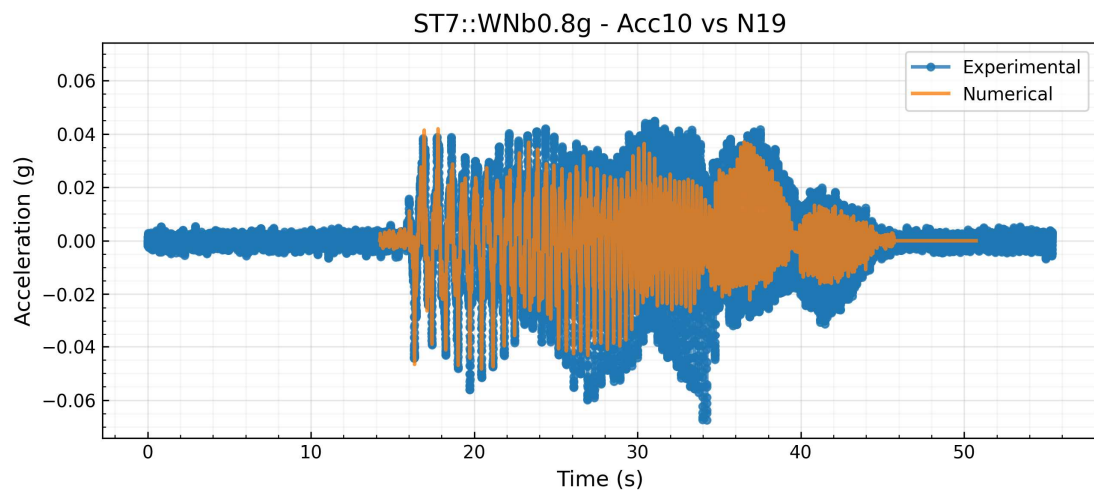


Figure 121 ST7 - Acceleration comparison Acc10 vs N19

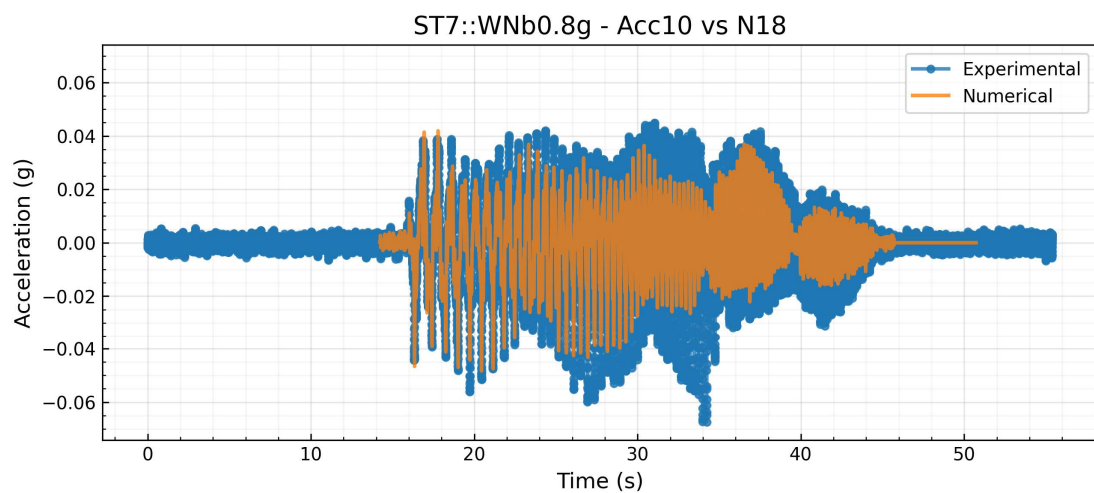


Figure 122 ST7 - Acceleration comparison Acc10 vs N18

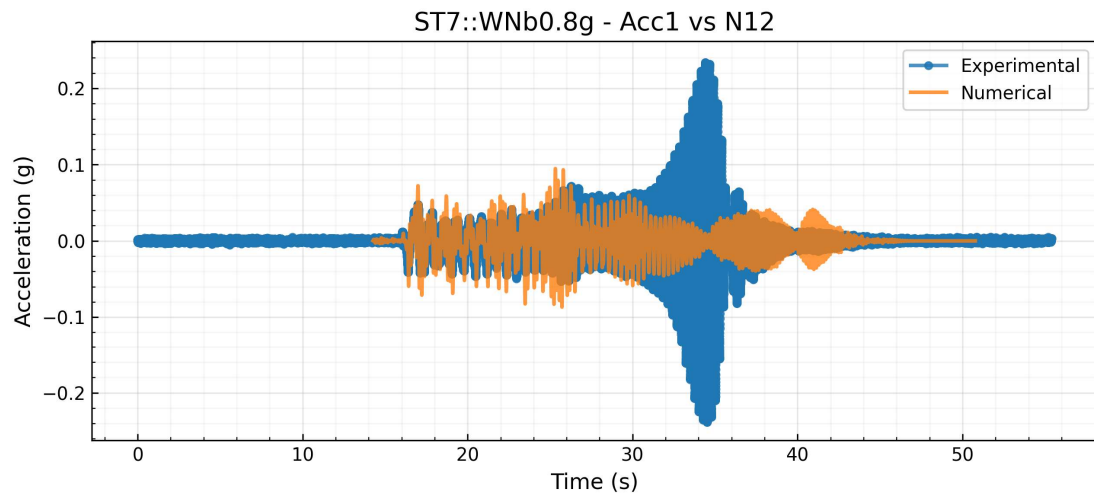


Figure 123 ST7 - Acceleration comparison Acc1 vs N12

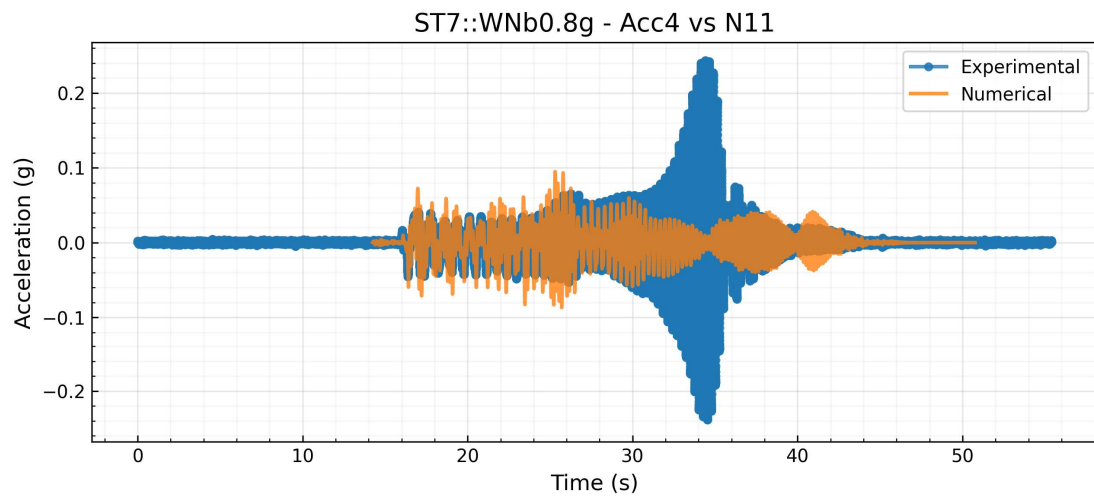


Figure 124 ST7 - Acceleration comparison Acc4 vs N11

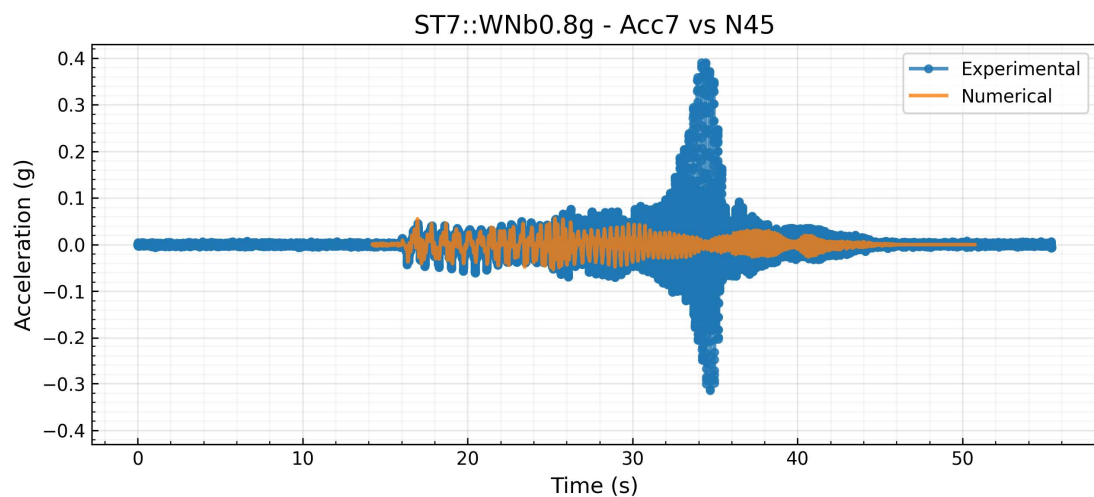


Figure 125 ST7 - Acceleration comparison Acc7 vs N45

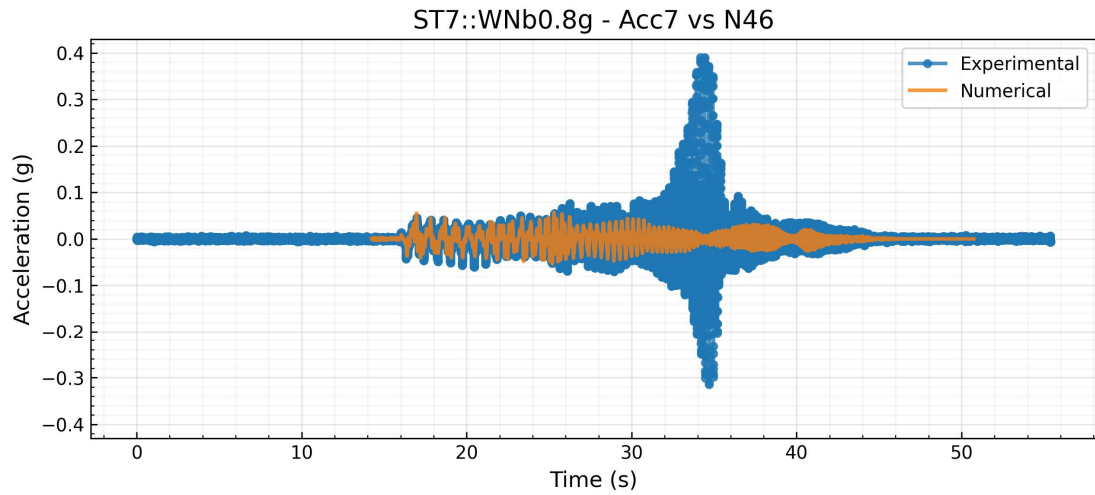


Figure 126 ST7 - Acceleration comparison Acc7 vs N46

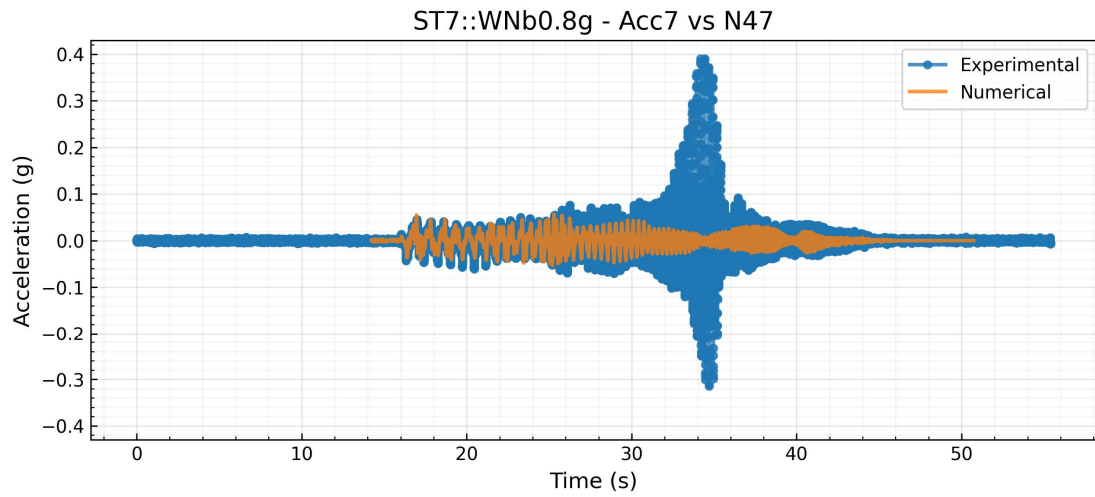


Figure 127 ST7 - Acceleration comparison Acc7 vs N47

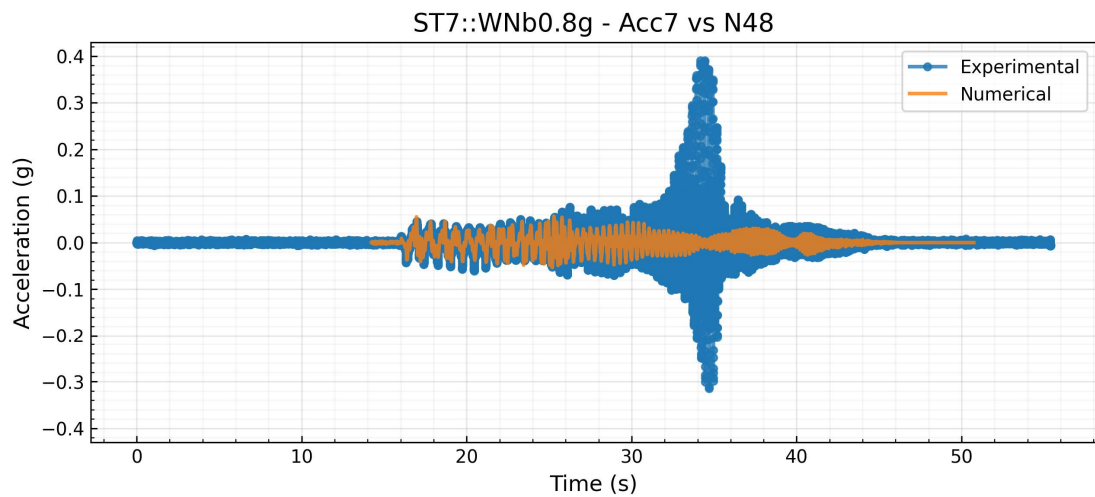


Figure 128 ST7 - Acceleration comparison Acc7 vs N48

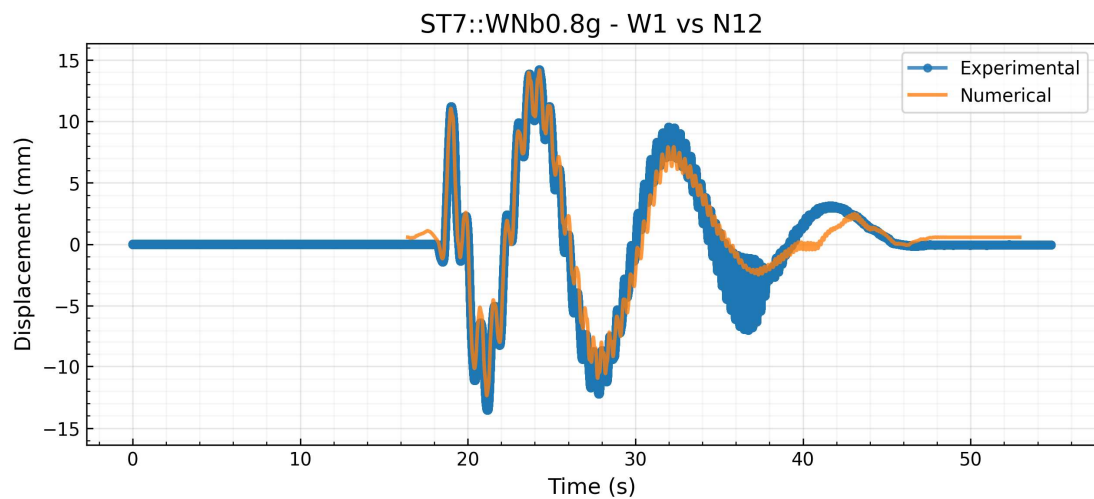


Figure 129 ST7 - Displacement comparison W1 vs N12

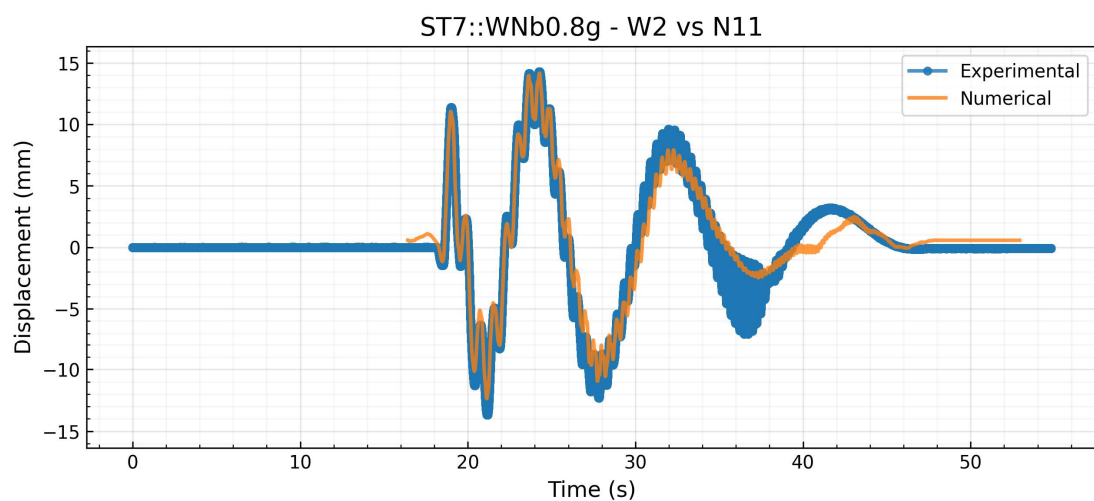


Figure 130 ST7 - Displacement comparison W2 vs N11

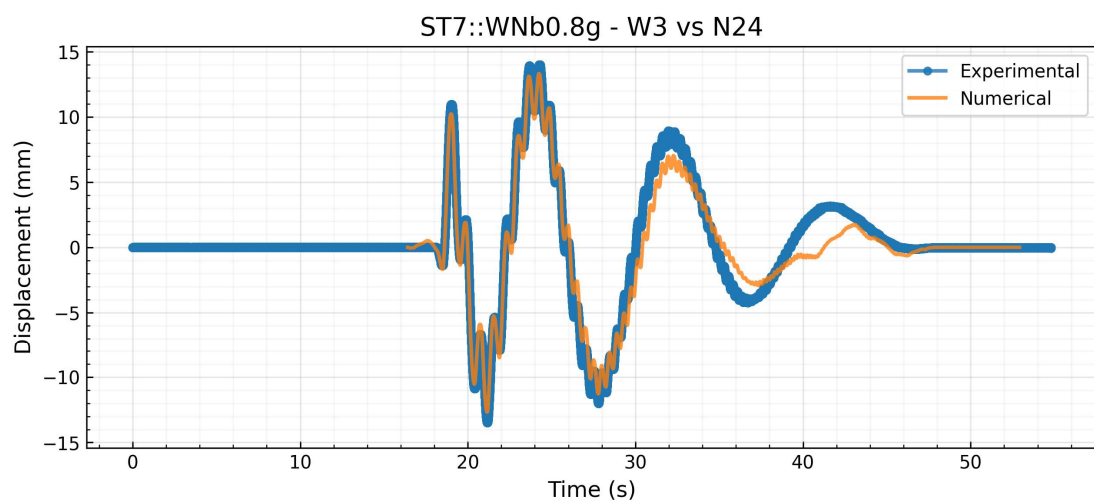


Figure 131 ST7 - Displacement comparison W3 vs N24

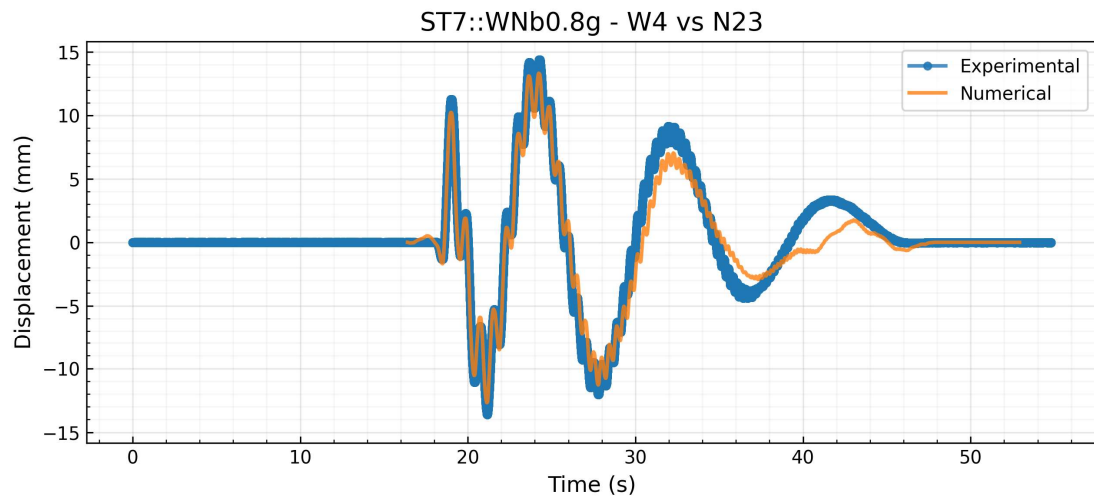


Figure 132 ST7 - Displacement comparison W4 vs N23

4.10 ST9::WNB1.1G RESULTS

The result for draw-wires and accelerometers for ST9::WNb1.1g are presented here.

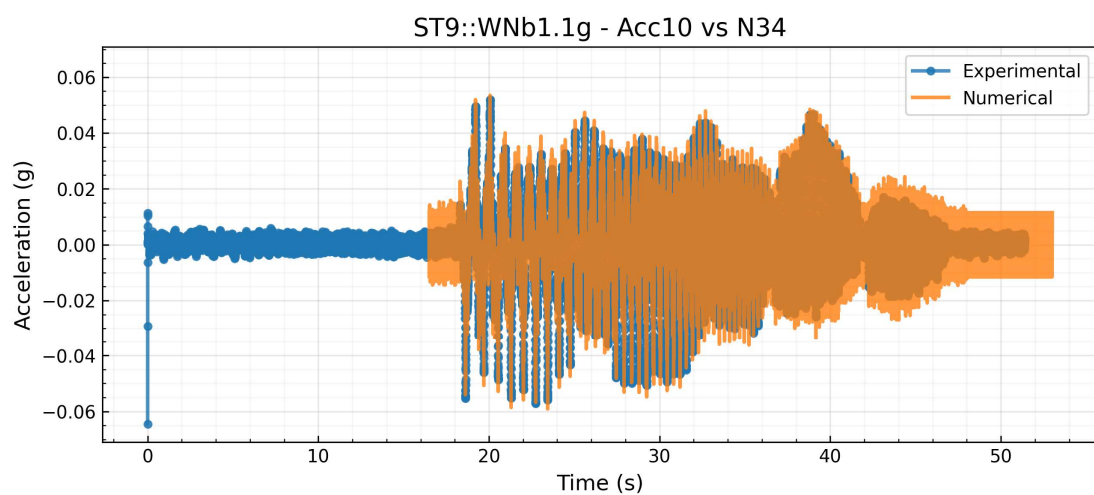


Figure 133 ST9 - Acceleration comparison Acc10 vs N34

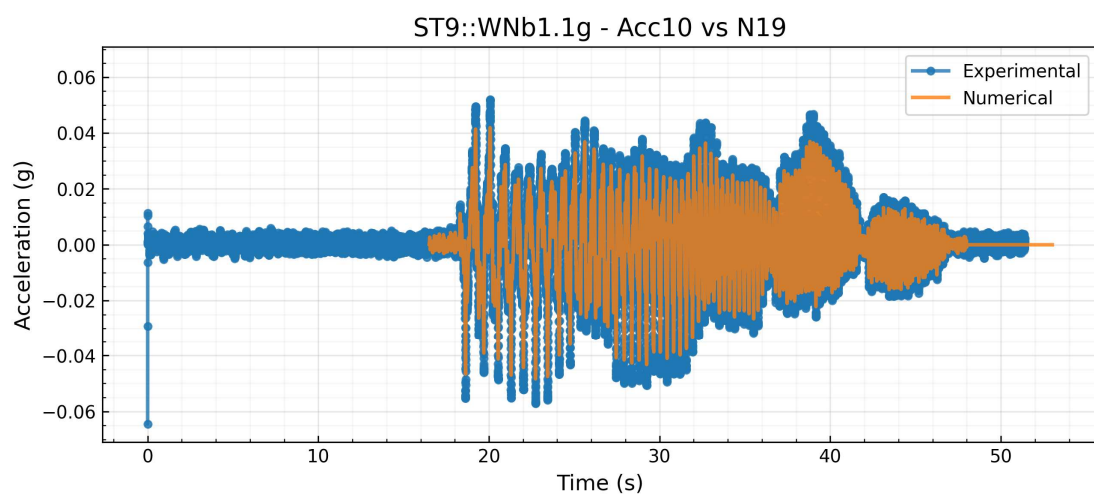


Figure 134 ST9 - Acceleration comparison Acc10 vs N19

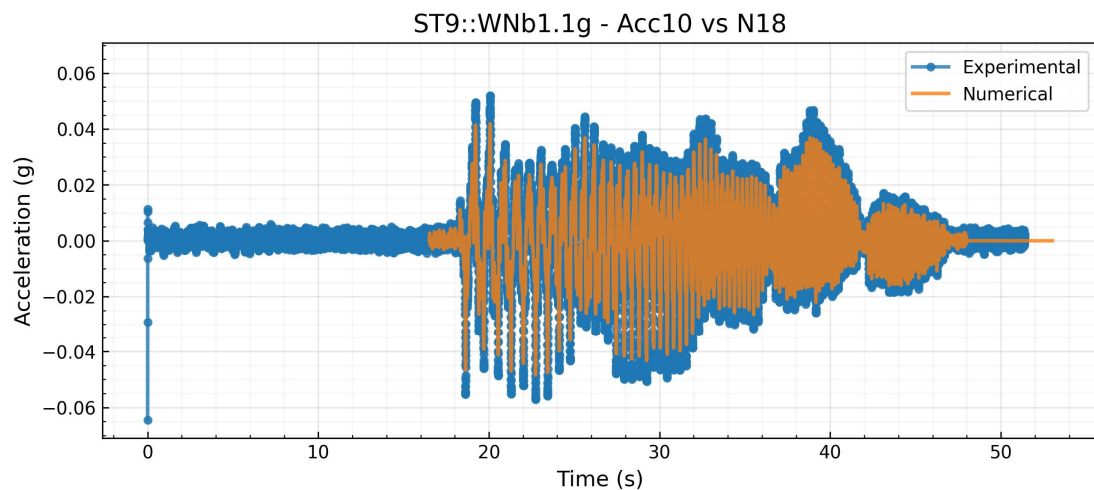


Figure 135 ST9 - Acceleration comparison Acc10 vs N18

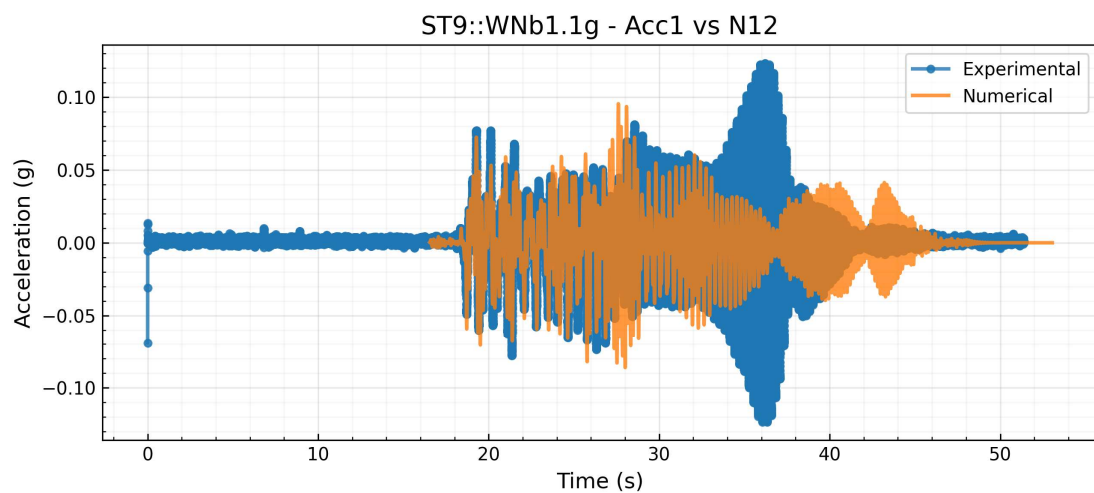


Figure 136 ST9 - Acceleration comparison Acc1 vs N12

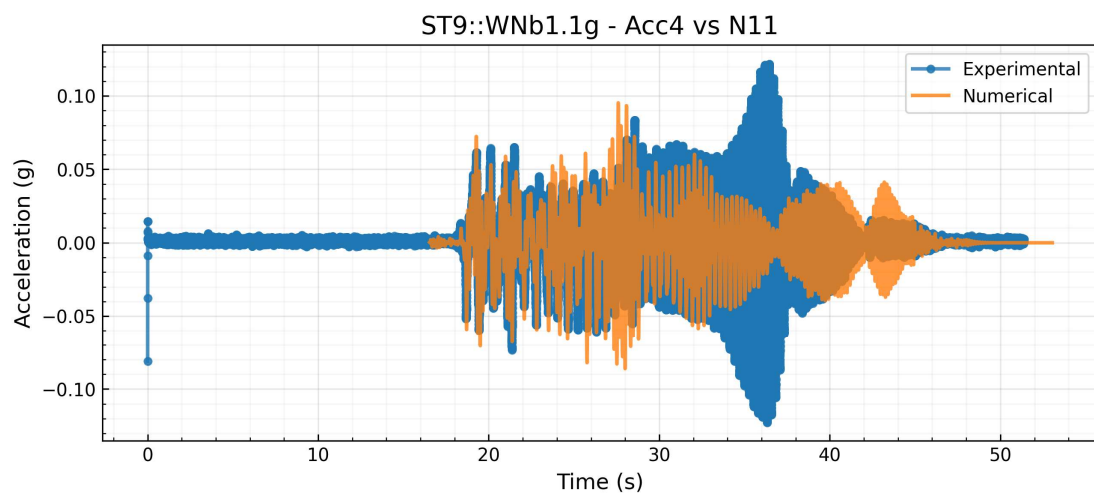


Figure 137 ST9 - Acceleration comparison Acc4 vs N11

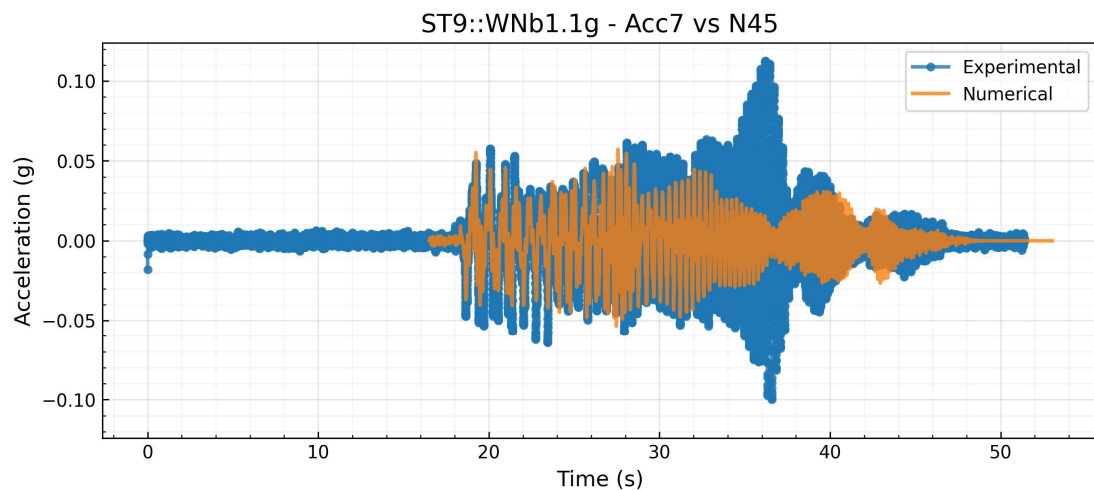


Figure 138 ST9 - Acceleration comparison Acc7 vs N45

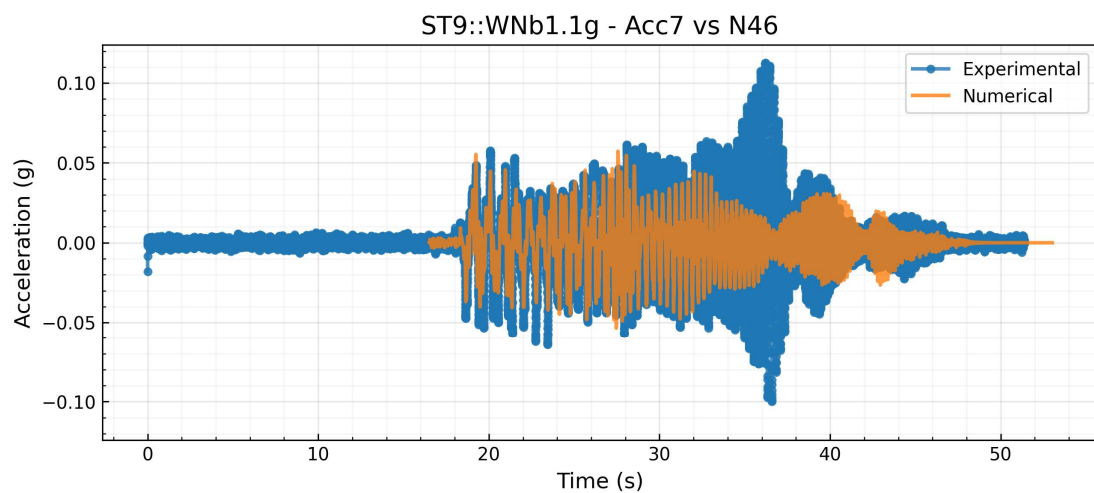


Figure 139 ST9 - Acceleration comparison Acc7 vs N46

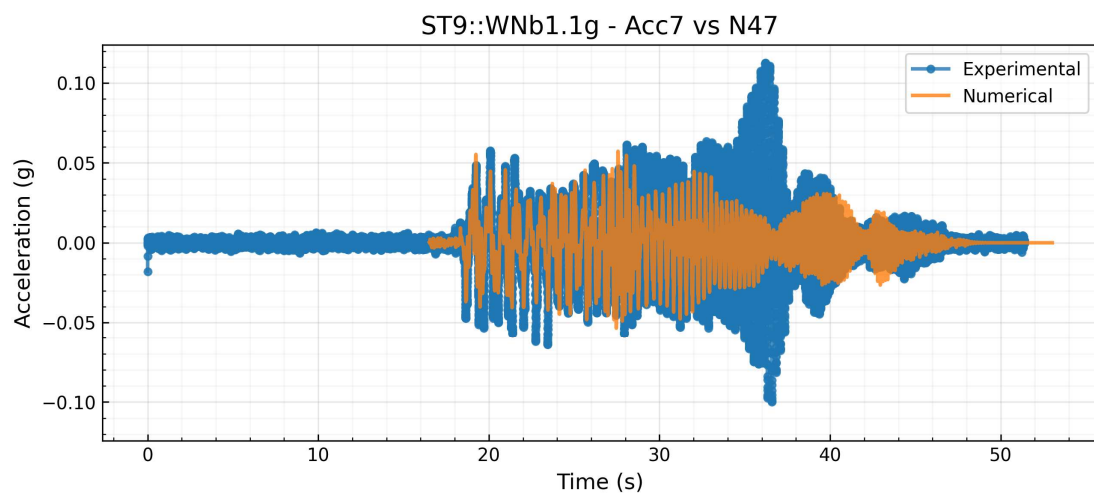


Figure 140 ST9 - Acceleration comparison Acc7 vs N47

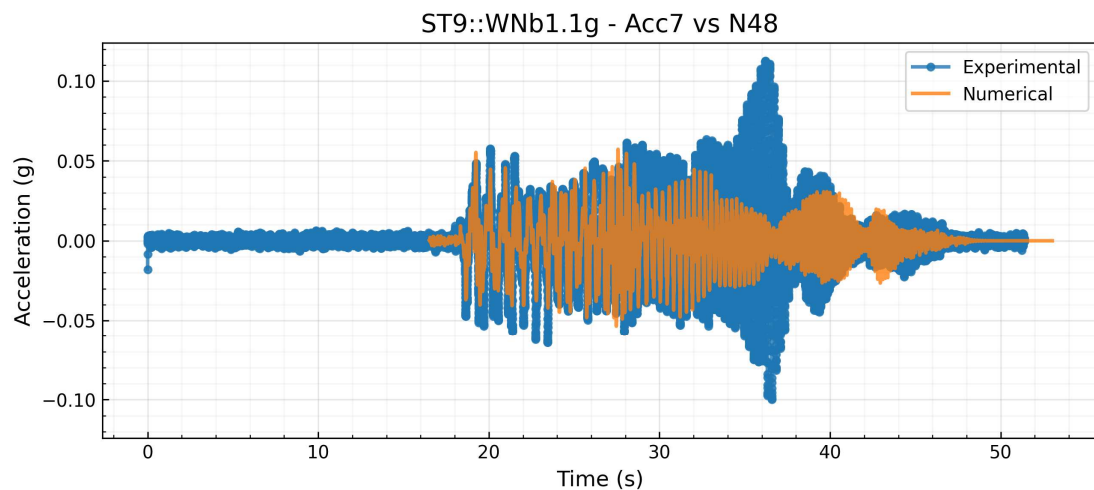


Figure 141 ST9 - Acceleration comparison Acc7 vs N48

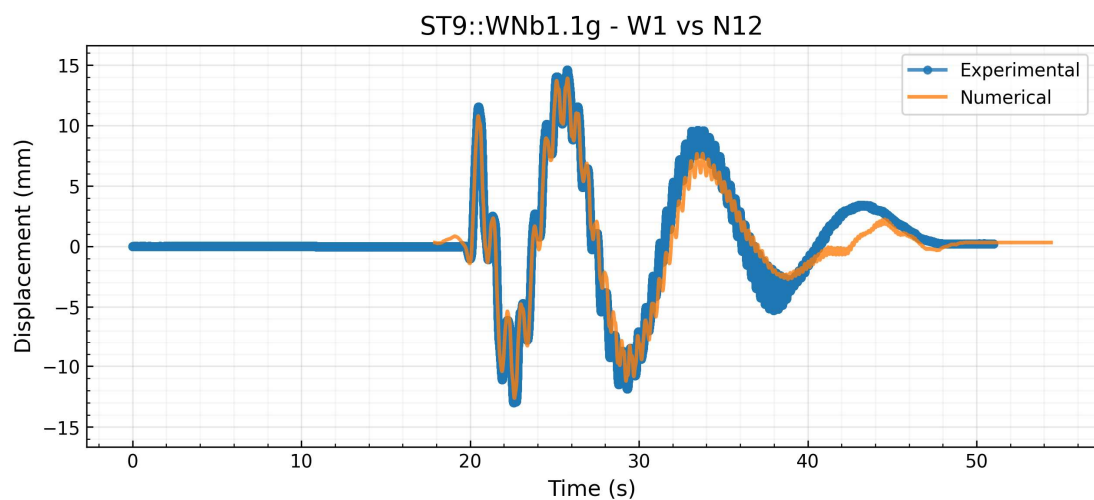


Figure 142 ST9 - Displacement comparison W1 vs N12

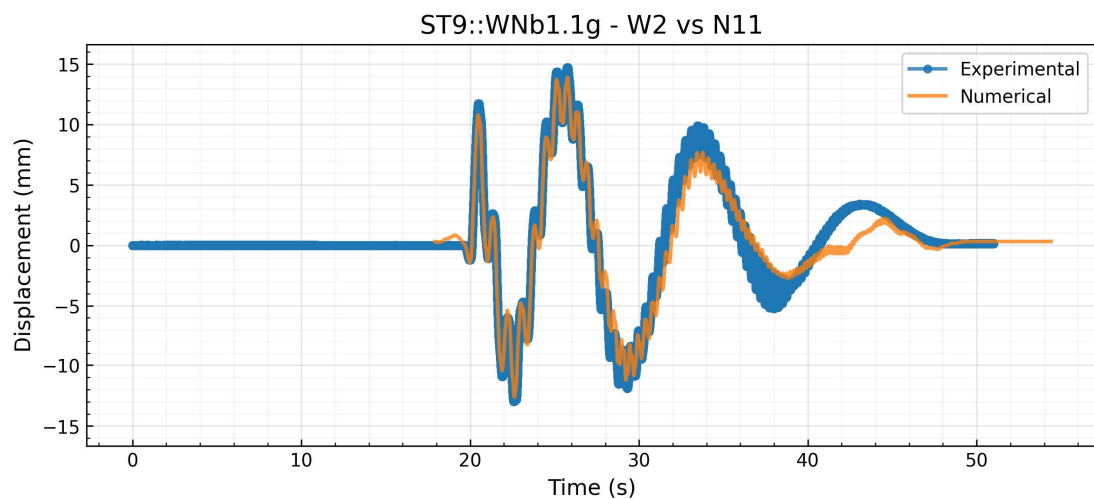


Figure 143 ST9 - Displacement comparison W2 vs N11

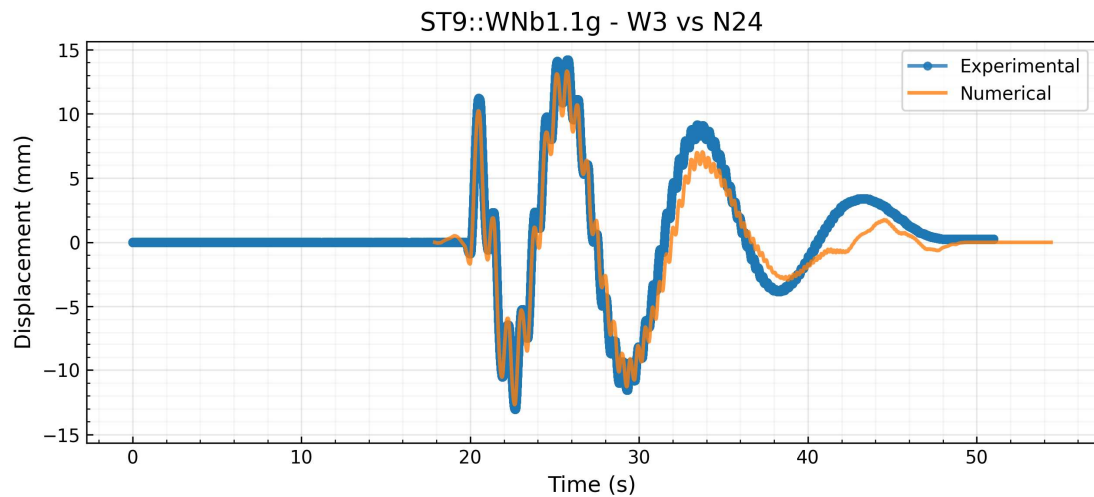


Figure 144 ST9 - Displacement comparison W3 vs N24

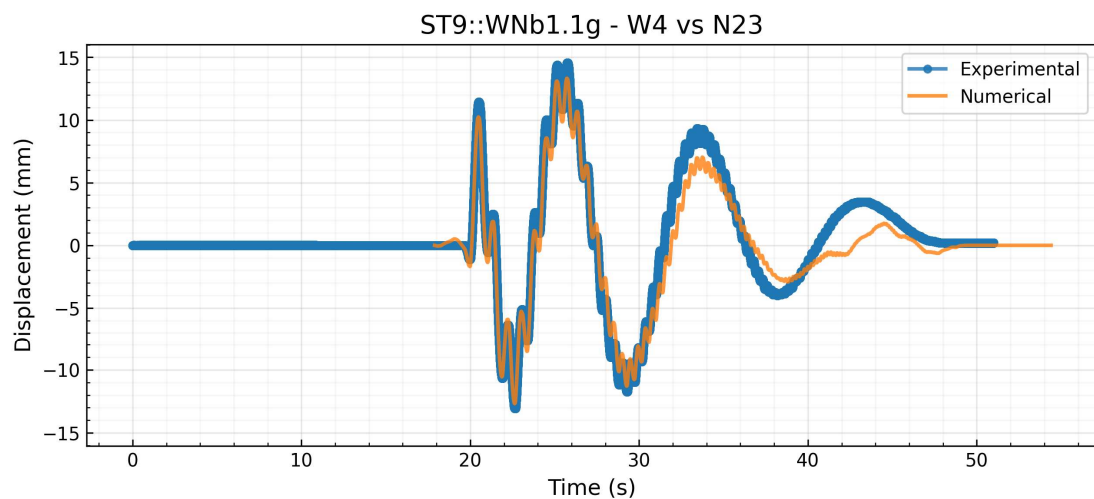


Figure 145 ST9 - Displacement comparison W4 vs N23

4.11 ST11:WNA1.1G RESULTS

The result for draw-wires and accelerometers for ST11::WNA1.1g are presented here.

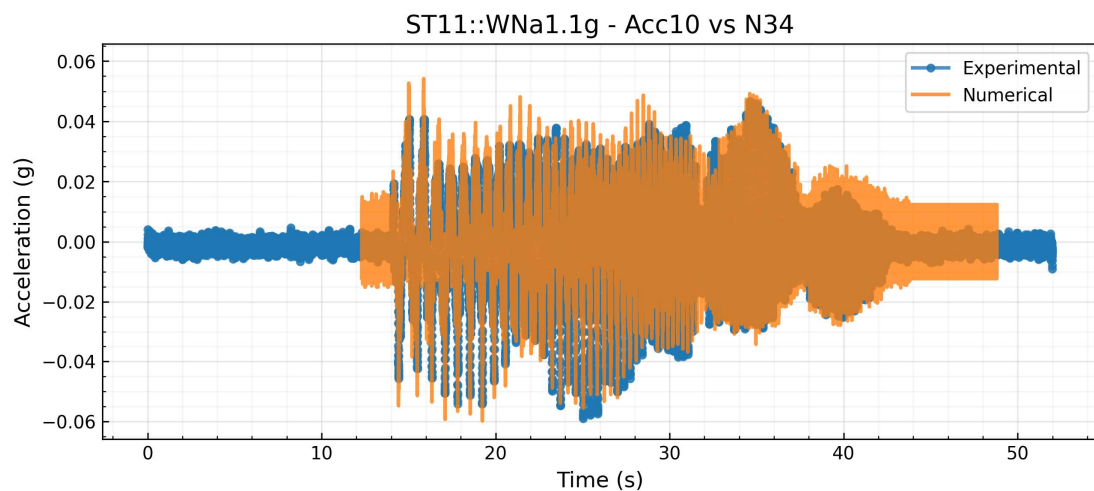


Figure 146 ST11 - Acceleration comparison Acc10 vs N34

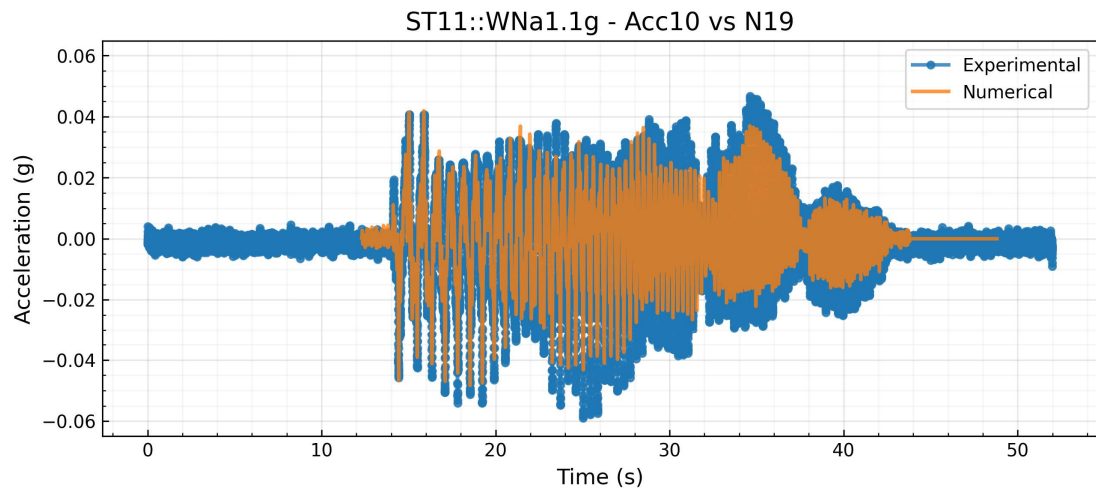


Figure 147 ST11 - Acceleration comparison Acc10 vs N19

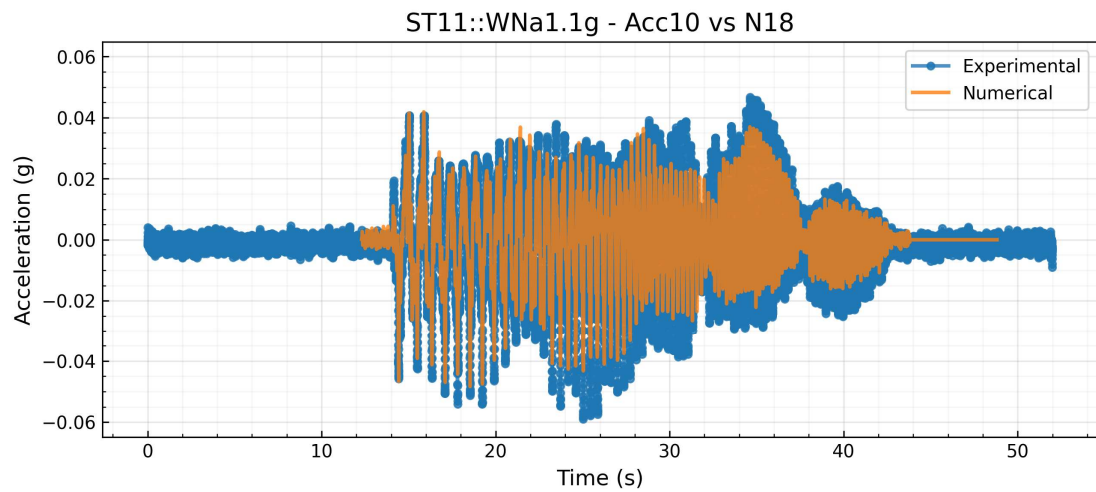


Figure 148 ST11 - Acceleration comparison Acc10 vs N18

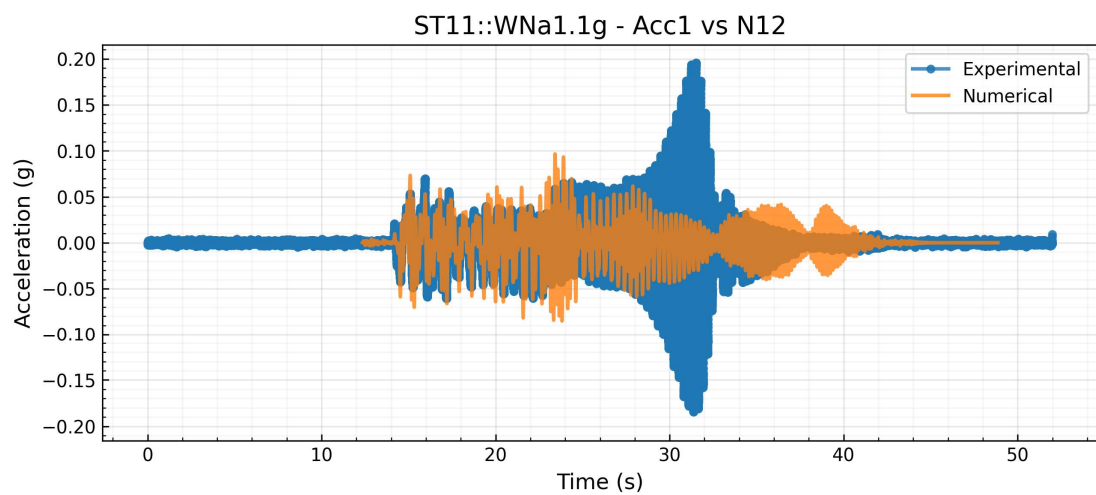


Figure 149 ST11 - Acceleration comparison Acc1 vs N12

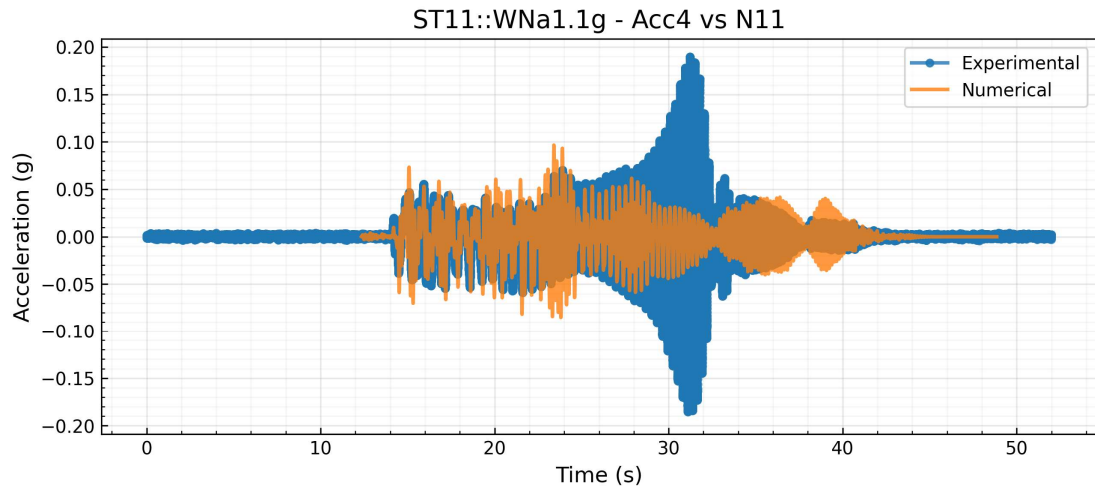


Figure 150 ST11 - Acceleration comparison Acc4 vs N11

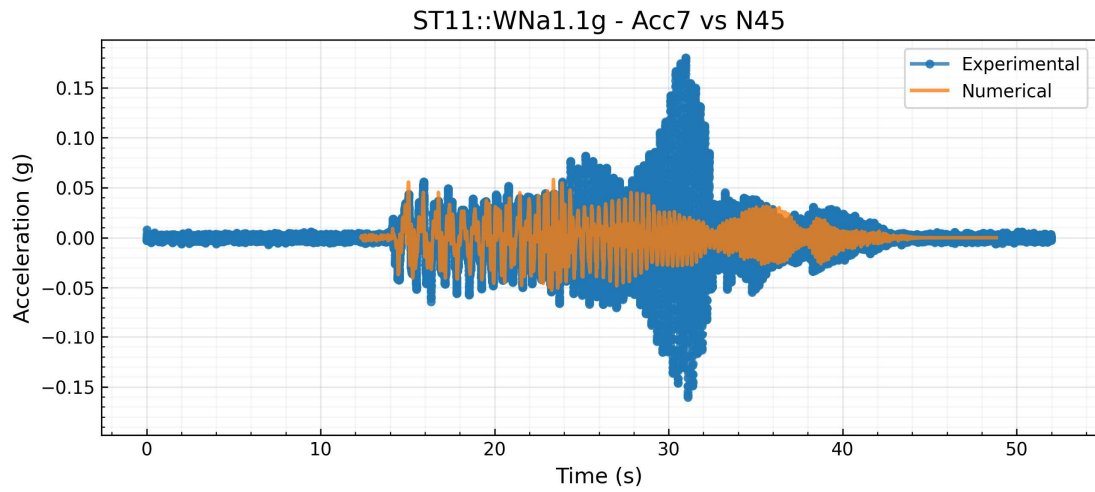


Figure 151 ST11 - Acceleration comparison Acc7 vs N45

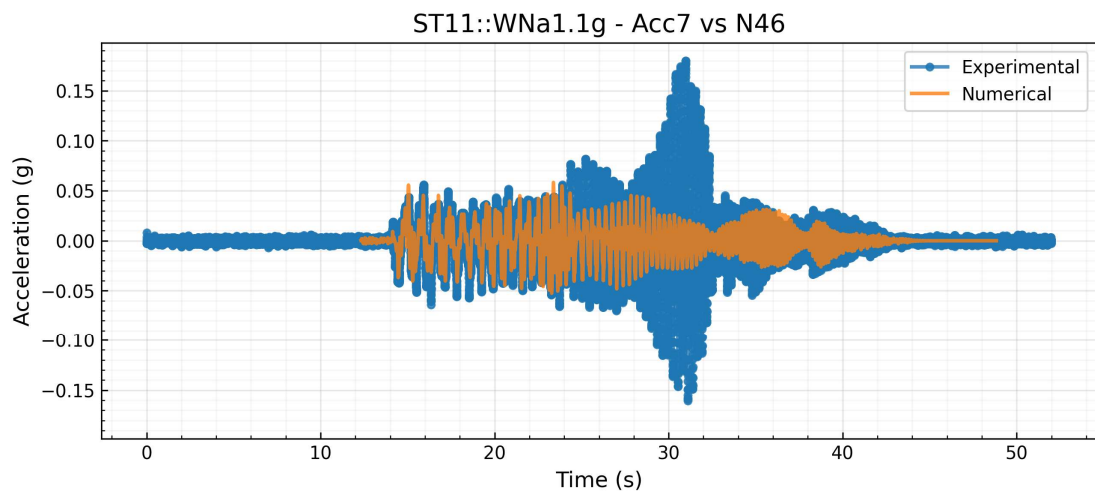


Figure 152 ST11 - Acceleration comparison Acc7 vs N46

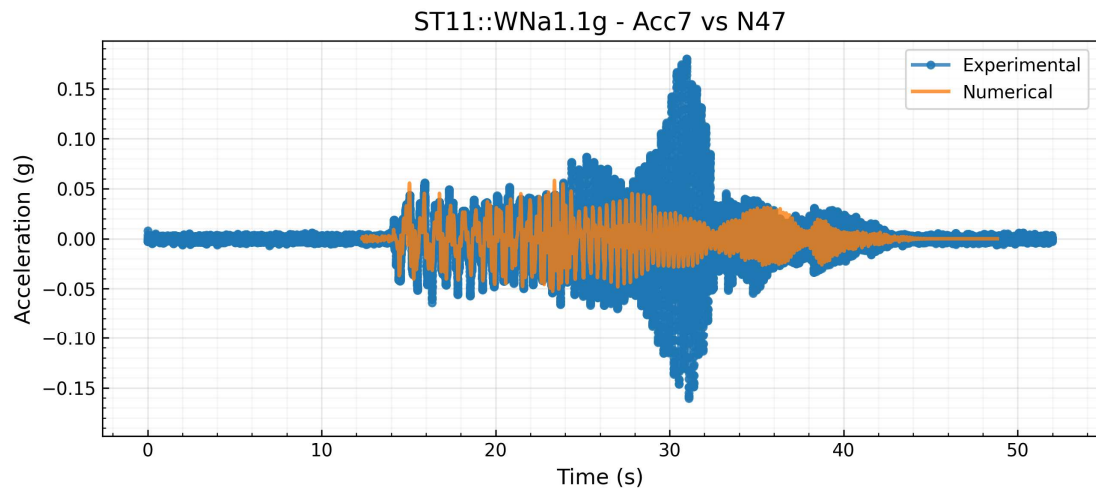


Figure 153 ST11 - Acceleration comparison Acc7 vs N47

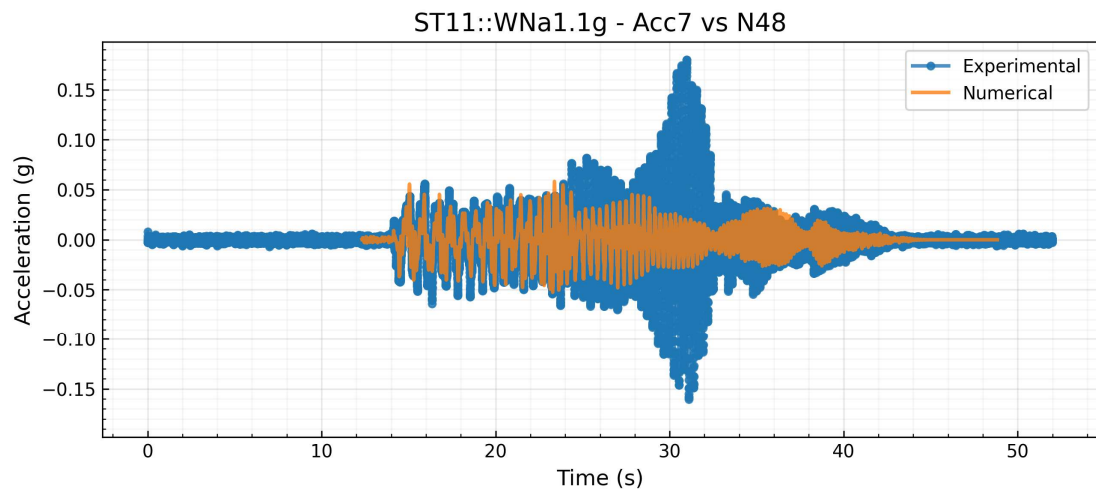


Figure 154 ST11 - Acceleration comparison Acc7 vs N48

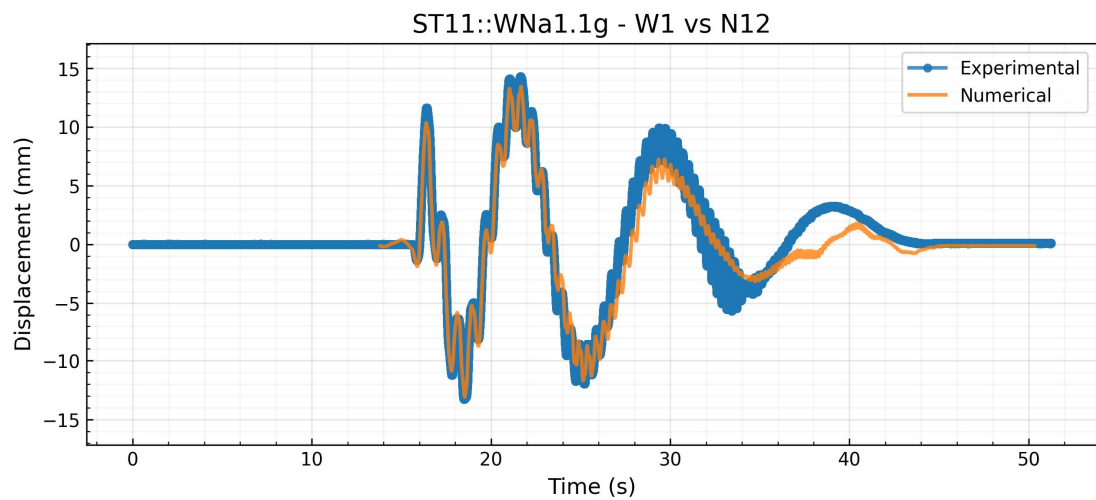


Figure 155 ST11 - Displacement comparison W1 vs N12

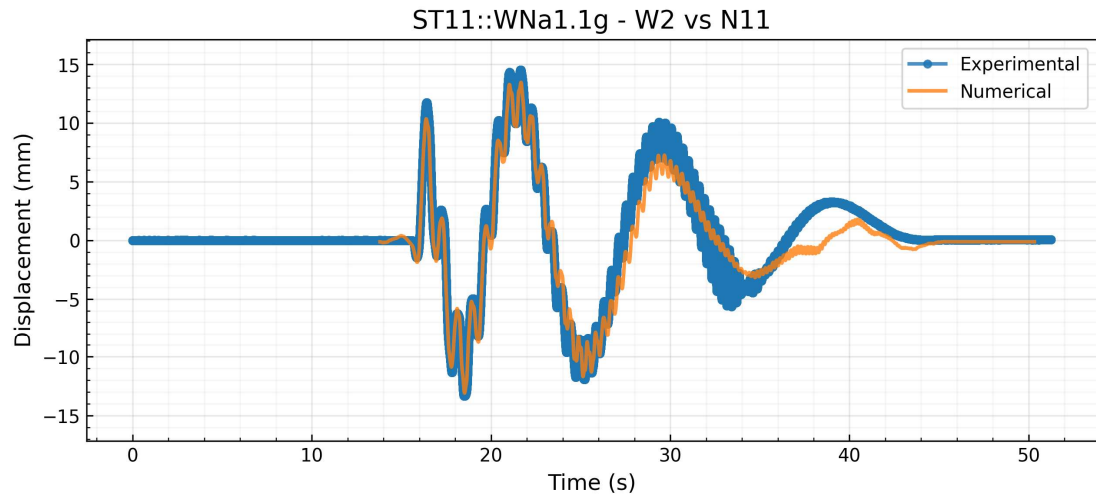


Figure 156 ST11 - Displacement comparison W2 vs N11

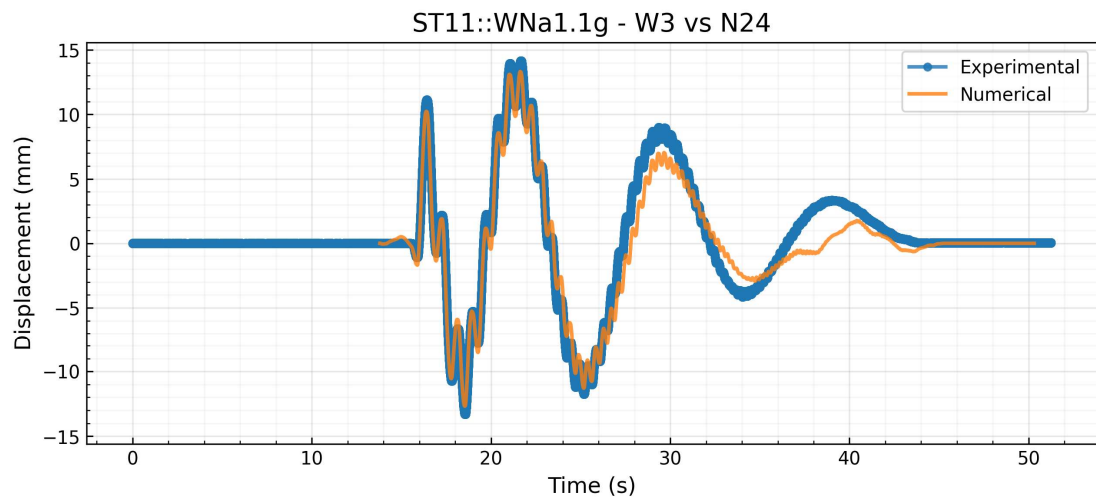


Figure 157 ST11 - Displacement comparison W3 vs N24

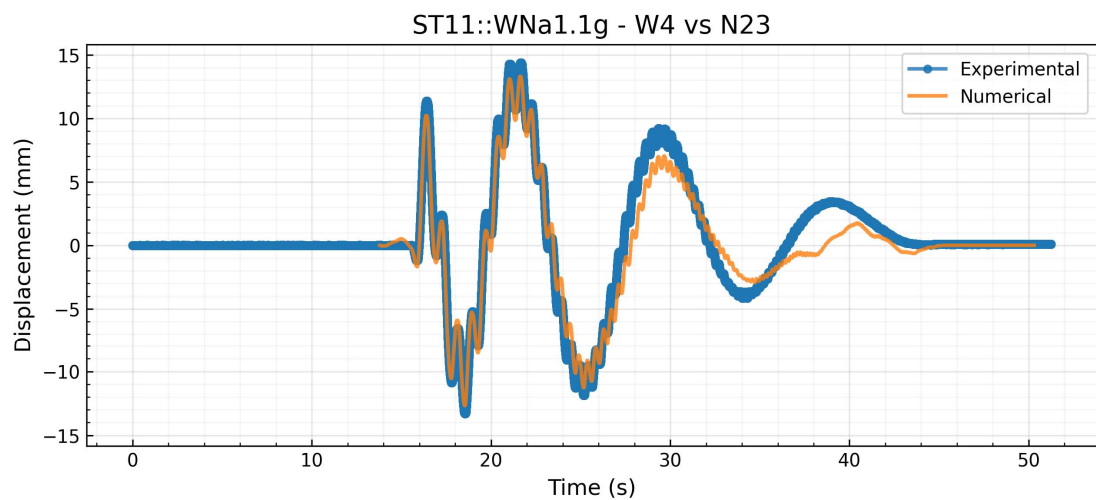
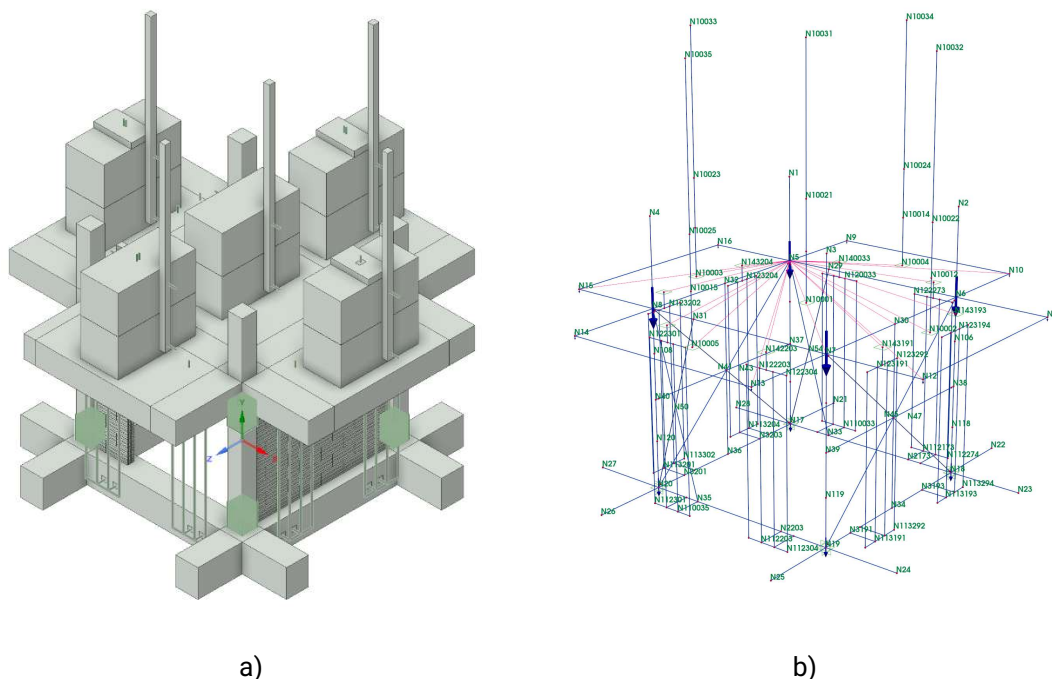


Figure 158 ST11 - Displacement comparison W4 vs N23

5 IMPLEMENTATION OF THE PUSHOVER TIME HISTORY ON THE RENOVATED 3D VF STRUCTURE

For the renovated structure additional nodes were introduced to the model for the critical connection interaction parts of the model. This includes base steel connection and rope basalt vertical top connection for the vertical living wall systems. Split the infill elements in the concrete-infill interface connection where PUFJ seismic joint were introduced. Predefined diaphragm nodes for the planters' (pods) location and the inclusion of vertical tree simulation. The characteristic transformation from the detailed 3D CAD model to the mathematical representation of the twin model is depicted in the Figure 159. Therefore, the developed digital twin model of the renovated construction reproduces the unique performance of materials, of their interfaces and interactions with distinctive structural and energy-forestry (vertical living walls and their fixings, planters and their fixings) sensitive parameters. That is, enabling for the modeling of the 3d reinforced concrete structure, of the green retrofits, of the green envelopes (greenery-forestry) and of their interactions towards real-time interoperability with physical model. ReplicaXLite, based on extensive basic research (TRL 1-3), includes all appropriate finite element models (and their calibration with available experiments as well as partial ANSYS Explicit Dynamics cross validation), especially for innovative green retrofit materials, green concrete-forestry interface envelopes, for instrumentation locations and types, for forestry and for their interactions and fixings. This advanced analytical framework enables for structural, energy and comfort related mathematical background integration.



stress/strain ratio, yielding 338 MPa. The fiber rope was modeled using a hollow fiber section through the StructuralAPI capabilities within ReplicaXLite software.

Vertical Living Wall (VLW) Components

The same material and section properties were combined with the forceBeamColumn element to accurately simulate the experimental specimen behavior. This configuration represented a composite rope securing the top portion of the steel vertical living wall (VLW). The VLW components were simulated using elastic steel material properties with sections of 10 mm and 20 mm diameters, using the StructuralAPI capabilities within ReplicaXLite software. No significant damage was anticipated in these elements, except for concentrated stresses at the base concrete and basalt rope interface, which were already captured by the fiber section definition of the previous defined elements.

Planter Pods and trees

The planter pods on top of the slab were simulated using hollow sections representing the majority of the pod geometry using the StructuralAPI capabilities within ReplicaXLite software. The material was initially defined as elastic, with the option to switch to fiber modeling if significant stress concentrations were observed during analysis. This did not occur. A wood elastic section with a 50 mm by 50 mm cross section was added extending from the pod section. Within the hollow pod section, additional elements simulated the steel anchoring mechanism: one steel anchor for planter 1 and basalt ropes for the remaining planters.

FRPU Infill Section

For the infill section, the properties of the mesh (SikaWrap®-350G Grid) and resin polyurethane PS were combined using a mix-rule material model and simulated as an external jacket in the outer region with thin layer of 3mm.

PUFJ Seismic Joint Region

For the seismic joint region, in which the brick infill wythe region, was removed from the original experimental setup (construction of the vertical gaps, Phase A), the same modeling approach was followed. During the Phase A, the regions of the seismic joint had already introduced the modeling features, required for the Phase B, but they had been assigned with brick infill-mortar properties. Then, during the Phase B, the PUFJ material sections and properties were updated in both StructuralAPI and OpenSeesPy. Therefore, they were reintroduced with the same cross-sectional properties as the removed infill parts but with specific PUFJ material definitions. The EPP material model in OpenSeesPy was utilized, with a 4 MPa elastic modulus and 110% elongation limit.

For all elements sharing common strengthening nodes (columns, infill, and planters), additional elements with identical start and end nodes were incorporated to capture the influence of these new components on both local and global behavior. The final representation of the linear digital twin model is depicted in Figure 159.

The masses were distributed appropriately in the top region of the planters and wooden sticks for the vertical forest simulation (see Table 5).

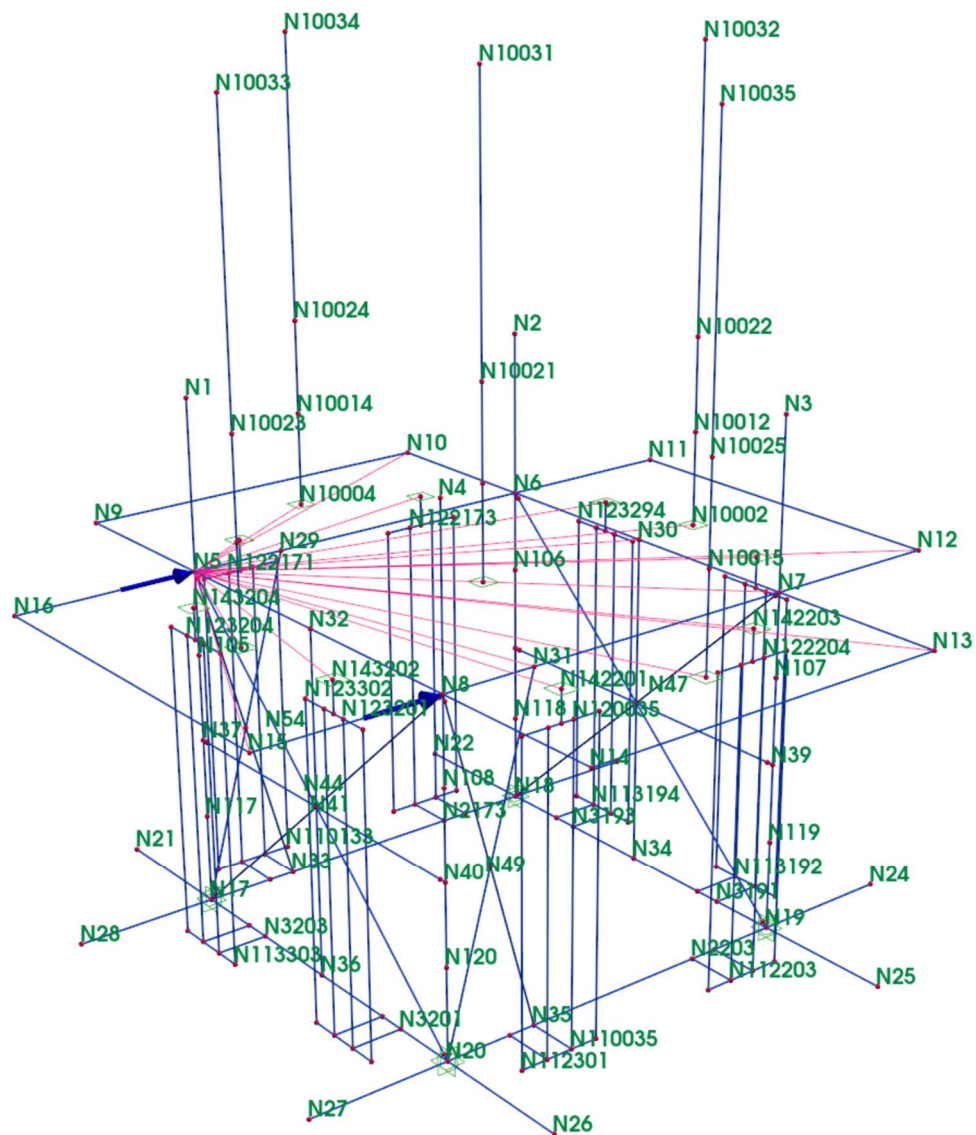
Table 5 Mass distribution table for renovated model

Group	Mass (kg)	Mass Portion (%)	Nodes
Top Column Corners	41.29	0.8	1-4
Beam-Column Joints	2075.44	40.05	5-8
Cantilever Edges	798.39	15.41	9-16
Bottom Beam-Column Joints	979.00	18.89	17-20
Base Beam Edges	223.59	4.31	21-28
Full Infills	157.98	3.05	41-48
Partial Infills	38.22	0.74	49-50, 53-54
Planters	765	14.76	10001-10025
Wooden Sticks	7	0.14	10031-10035
Steel frames for VLW	96	1.85	11XXXX, 12XXXX (no uniform numbering)
Total	5,181.91	100	1-50, 53-54

The pushover analysis was implemented as a static nonlinear analysis procedure to evaluate the seismic performance of the as-built structure under lateral loading conditions. This method involves applying incremental lateral loads to the structure while monitoring its response until desired displacement is reached. The `run_pushover_analysis` command from the ReplicaXLite API was used. The key implementation steps are:

- **Load Pattern Creation:** A new load pattern was created with a linear time series to simulate progressive lateral loading
- **Control Node Selection:** Node 5 was selected as the control node for the pushover analysis, with degree of freedom 1 (X-direction) being monitored
- **Loading Protocol:** The analysis employed a target protocol approach with a maximum displacement step of 0.033 meters divided into 100 increments
- **Analysis Parameters:** The standard OpenSees analysis parameters were used with default convergence criteria

The lateral loads were applied to nodes 5 and 8 as depicted in Figure 160. The result of the Pushover analysis is depicted in Figure 161.



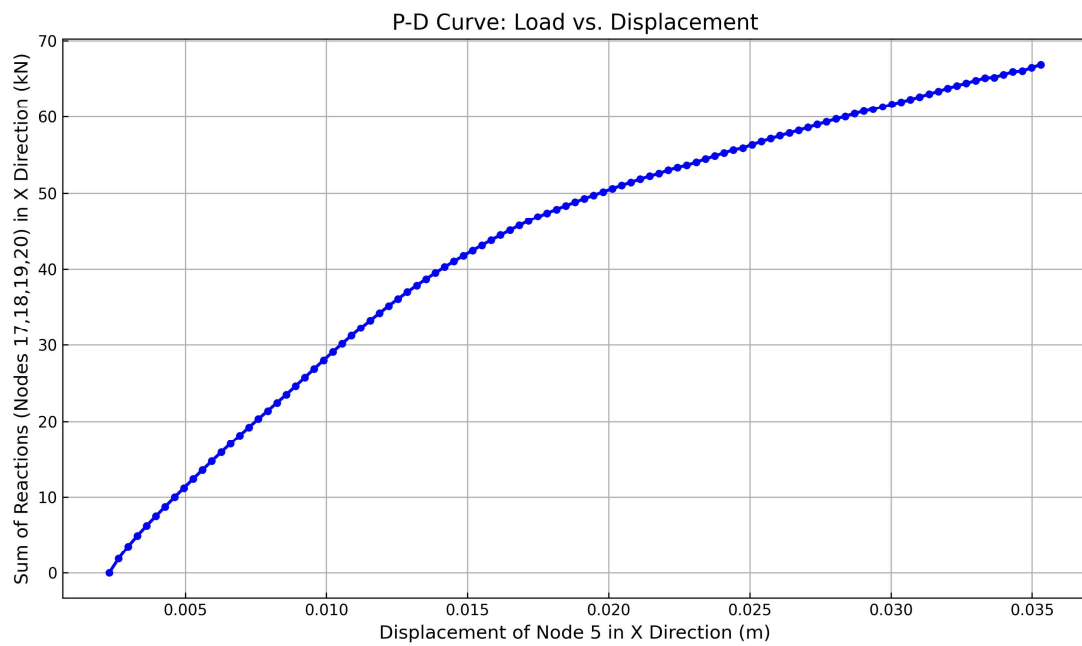


Figure 161 Pushover analysis result for the renovated structure

6 IMPLEMENTATION OF THE DYNAMIC TIME HISTORY ON THE RENOVATED 3D VF STRUCTURE

For the implementation of the dynamic time history analysis of the renovated model, the same model as in the pushover analysis was used, with the one difference that after the load Phase A, a series of continuous excitations of the experimental Phase B was applied in the fixed nodes. The sequence of the loading that was applied is presented in Table 6.

Table 6 Loading sequence for the numerical model

Test No.	Name	Type	Intensity	Test No.	Name	Type	Intensity
ST1	WNb0.07g (without)	White noise	0.05g	ST15	EQ0.74g	Earthquake	0.74g
ST2	WNb0.07g	White noise	0.05g	ST16	WNb0.8g	White noise	0.08g
ST3	EQ0.07g	Earthquake	0.07g	ST17	EQ0.8g	Earthquake	0.80g
ST4	EQ0.1g	Earthquake	0.10g	ST18	WNb1.1g	White noise	0.08g
ST5	WNb0.14g	White noise	0.08g	ST19	EQ1.1g	Earthquake	1.10g
ST6	EQ0.14g	Earthquake	0.14g	ST20	WNb1.3g	White noise	0.08g
ST7	EQ0.2g	Earthquake	0.20g	ST21	EQ1.3g	Earthquake	1.30g
ST8	WNb0.34g	White noise	0.08g	ST22	WNb1.3g(2)	White noise	0.08g
ST9	EQ0.34g	Earthquake	0.34g	ST23	EQ1.3g(2)	Earthquake	1.30g
ST10	WNb0.5g	White noise	0.08g	ST24	WNb 1.4g	White noise	0.08g
ST11	EQ0.5g	Earthquake	0.50g	ST25	EQ1.4g	Earthquake	1.40g
ST12	WNb0.55g	White noise	0.08g	ST26	Wnb0.2g (2)	White noise	0.08g
ST13	EQ0.55g	Earthquake	0.55g	ST27	EQ0.2g (2)	Earthquake	0.20g
ST14	WNb0.74g	White noise	0.08g	ST28	Wna0.2g	White noise	0.08g

The result of the analysis is presented in the next sections.

6.1 ST3::EQ0.07G RESULTS

The result for draw-wires and accelerometers for ST3::EQ0.07g are presented here.

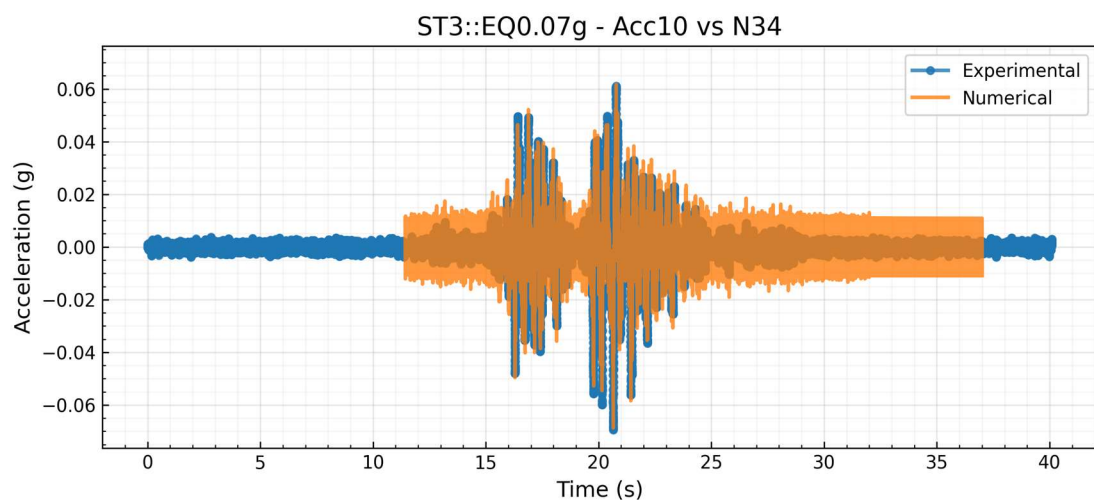


Figure 162 ST3 - Acceleration comparison Acc10 vs N34

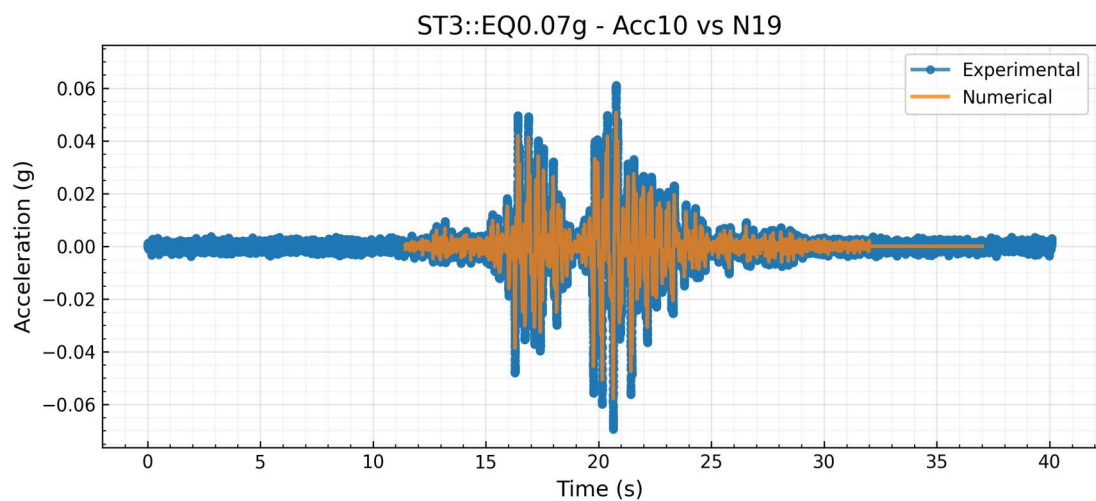


Figure 163 ST3 - Acceleration comparison Acc10 vs N19

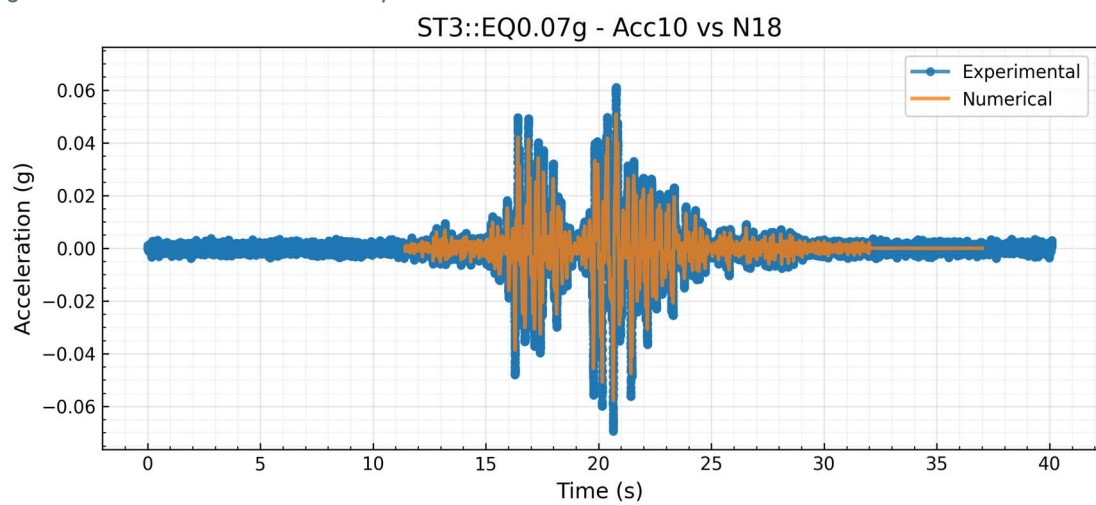


Figure 164 ST3 - Acceleration comparison Acc10 vs N18

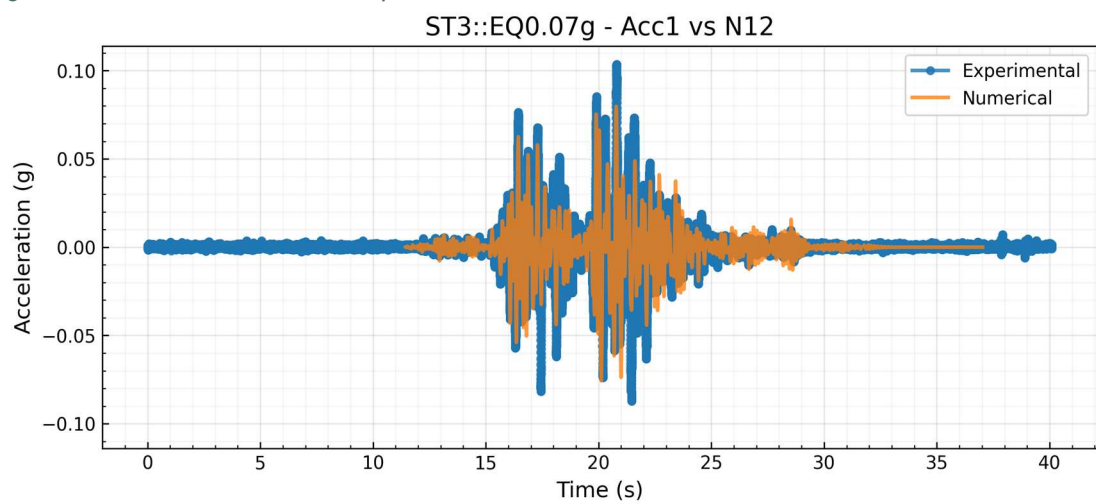


Figure 165 ST3 - Acceleration comparison Acc1 vs N12

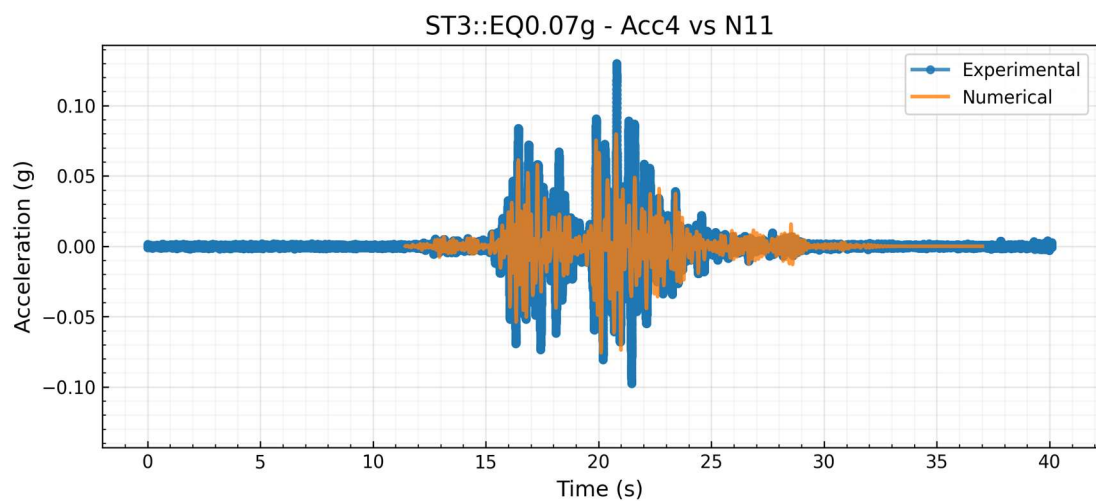


Figure 166 ST3 - Acceleration comparison Acc4 vs N11

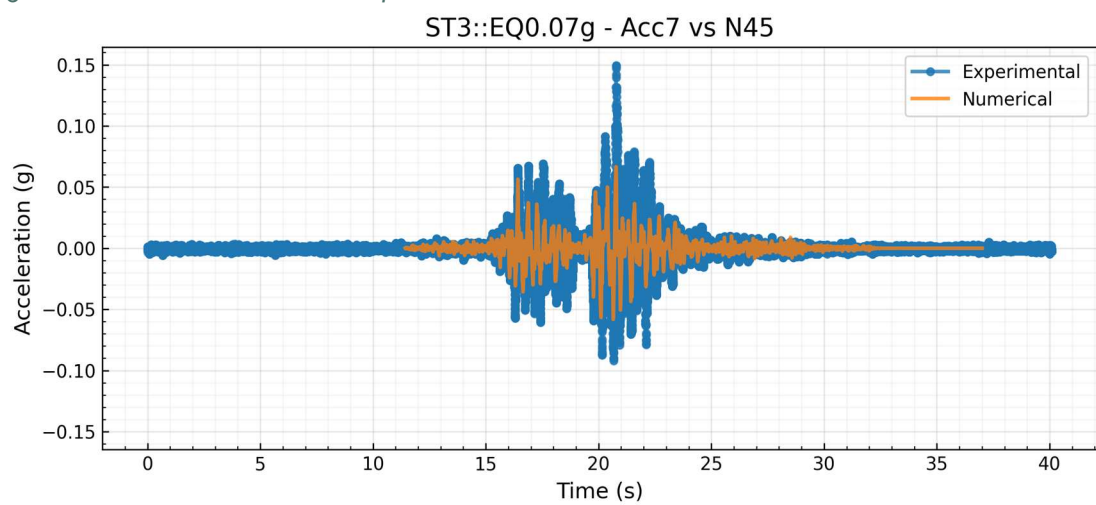


Figure 167 ST3 - Acceleration comparison Acc7 vs N45

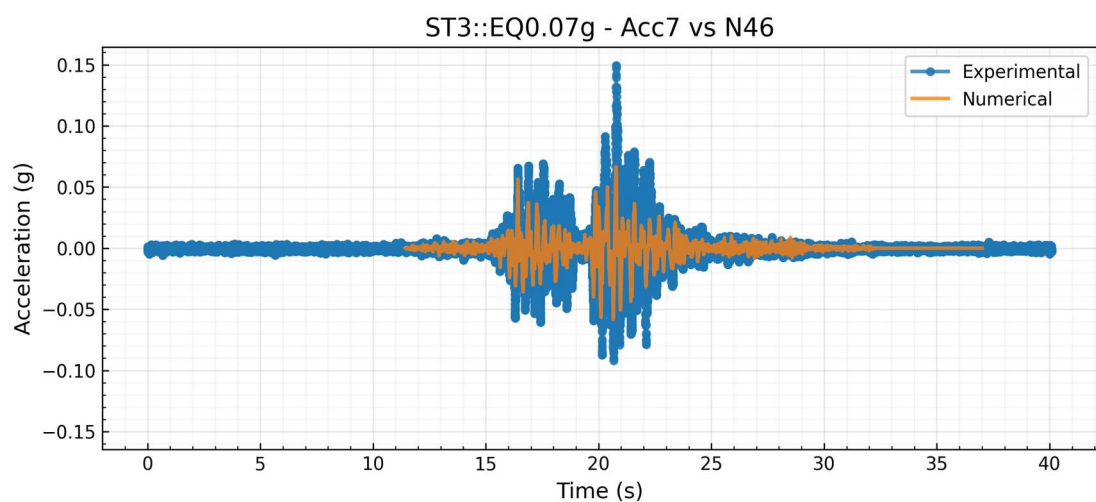


Figure 168 ST3 - Acceleration comparison Acc7 vs N46

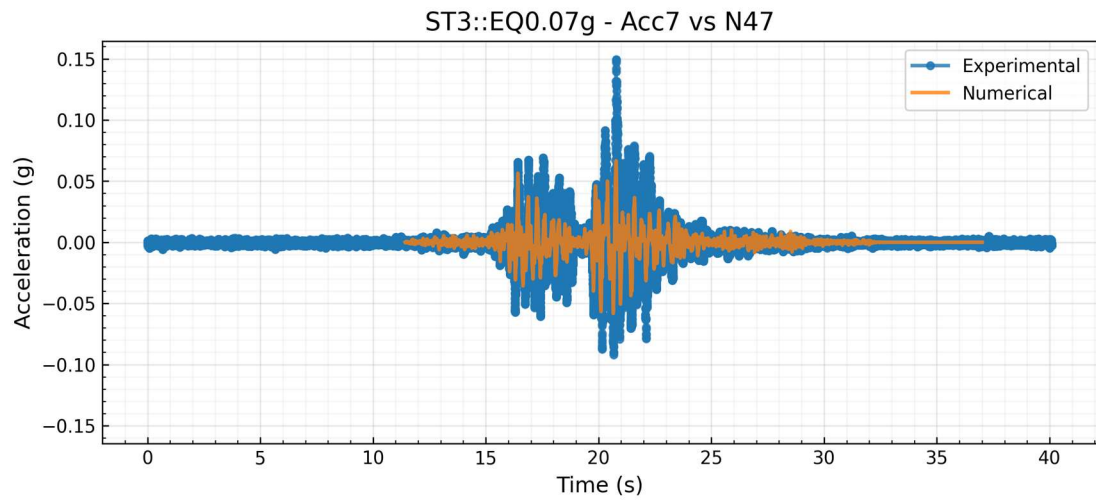


Figure 169 ST3 - Acceleration comparison Acc7 vs N47

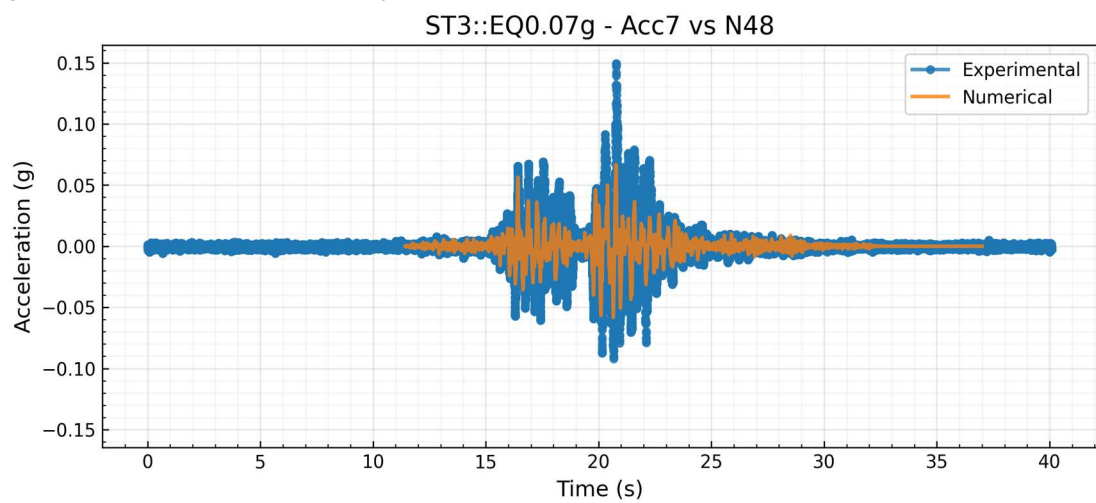


Figure 170 ST3 - Acceleration comparison Acc7 vs N48

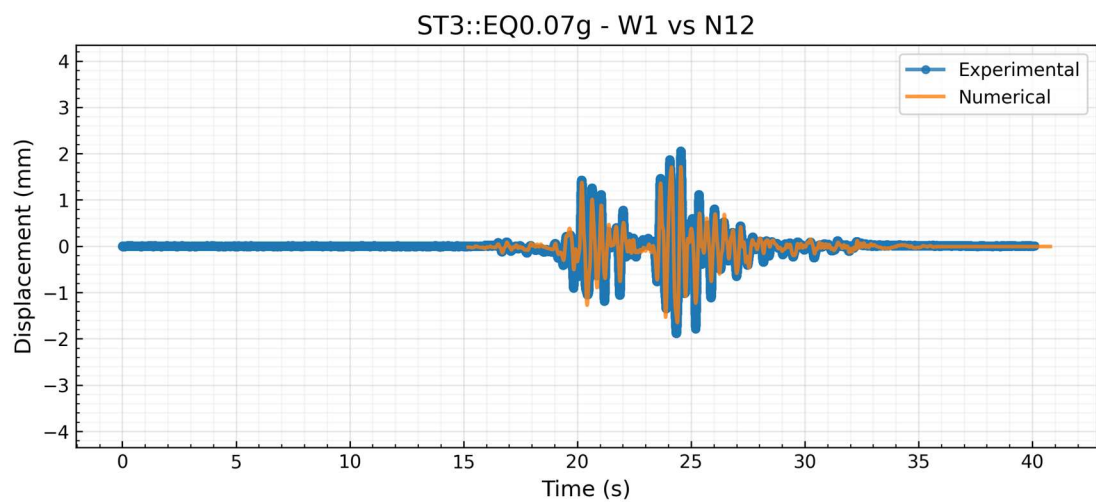


Figure 171 ST3 - Displacement comparison W1 vs N12

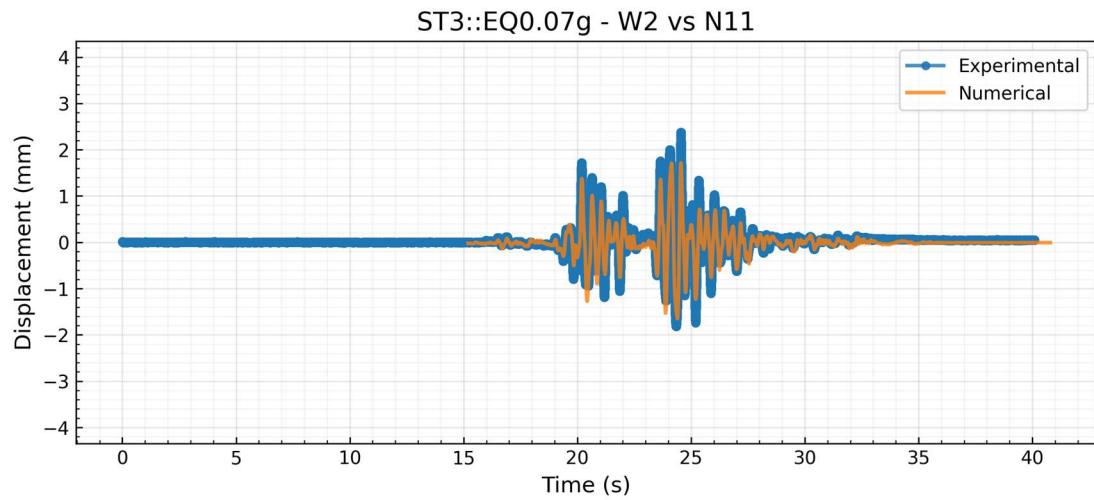


Figure 172 ST3 - Displacement comparison W2 vs N11

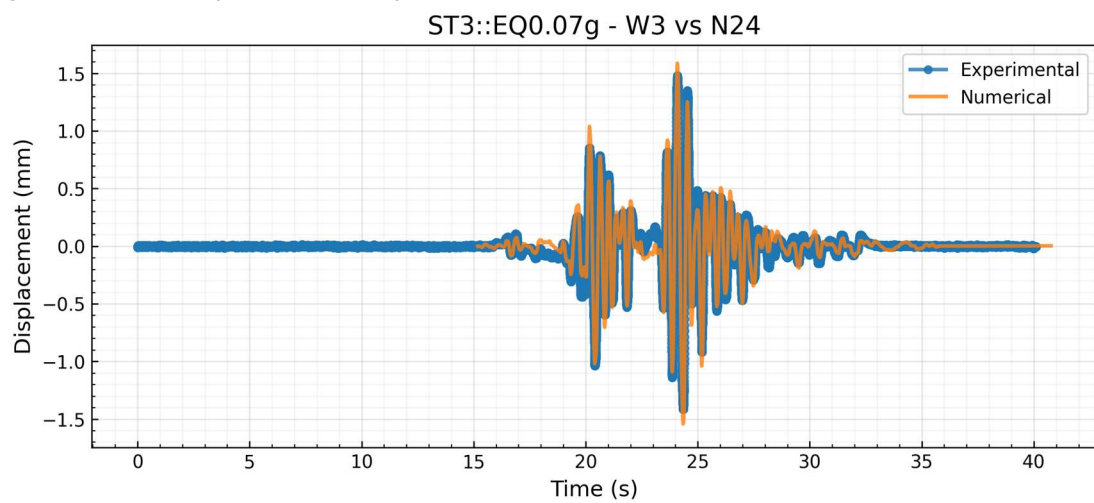


Figure 173 ST3 - Displacement comparison W3 vs N24

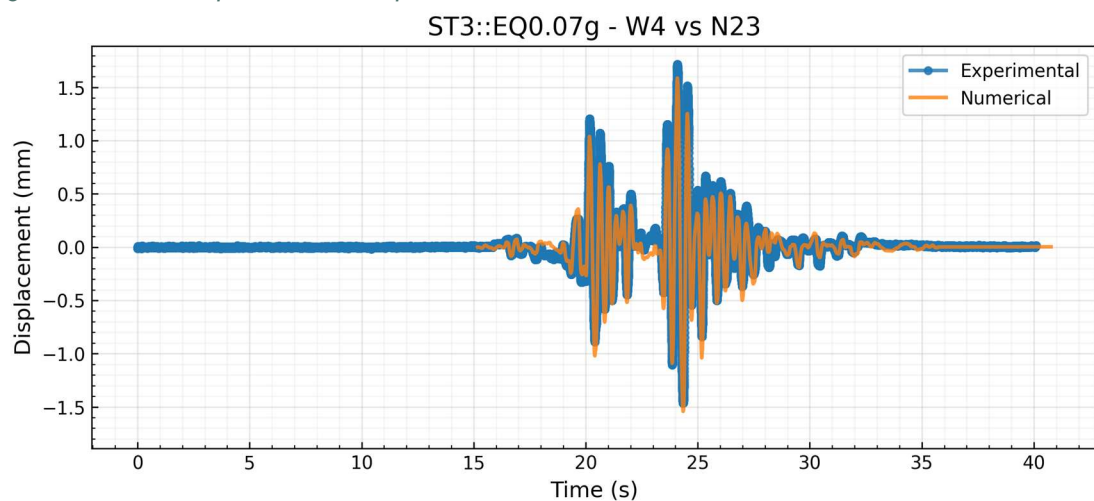


Figure 174 ST3 - Displacement comparison W4 vs N23

6.2 ST4::EQ0.1G RESULTS

The result for draw-wires and accelerometers for ST4::EQ0.1g are presented here.

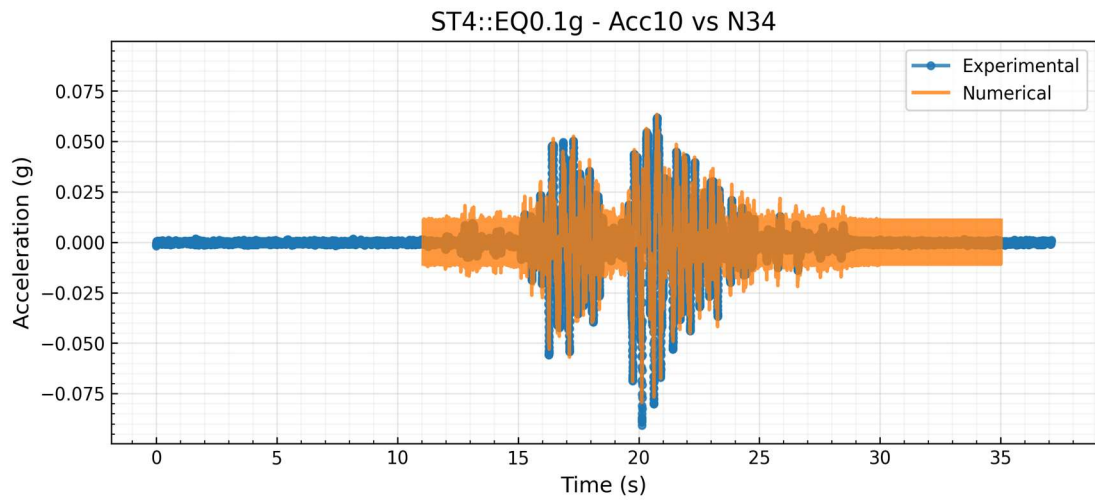


Figure 175 ST4 - Acceleration comparison Acc10 vs N34

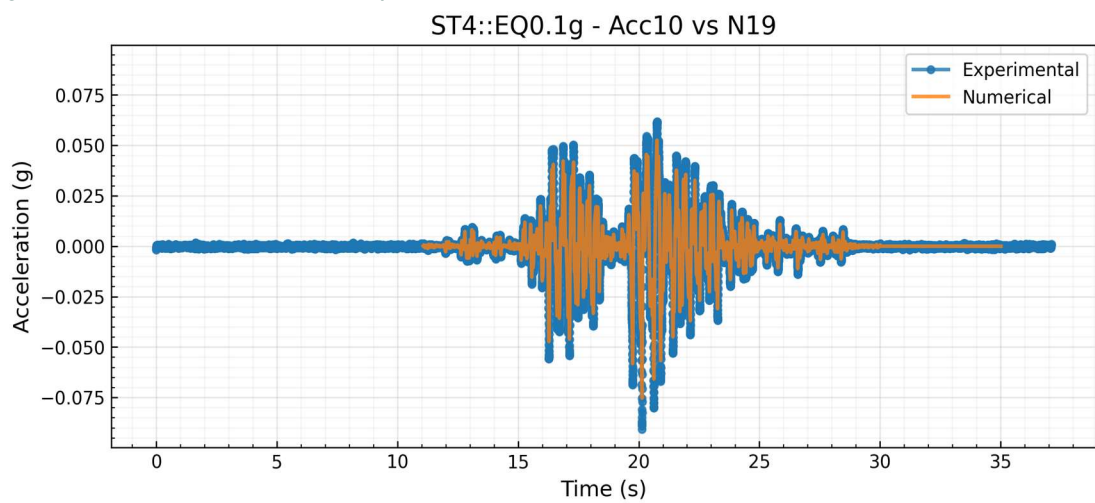


Figure 176 ST4 - Acceleration comparison Acc10 vs N19

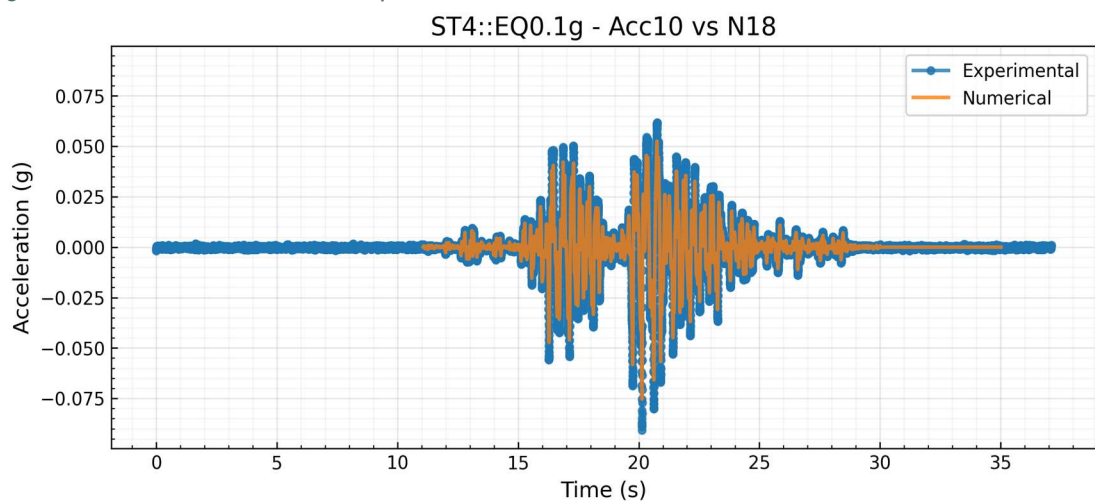


Figure 177 ST4 - Acceleration comparison Acc10 vs N18

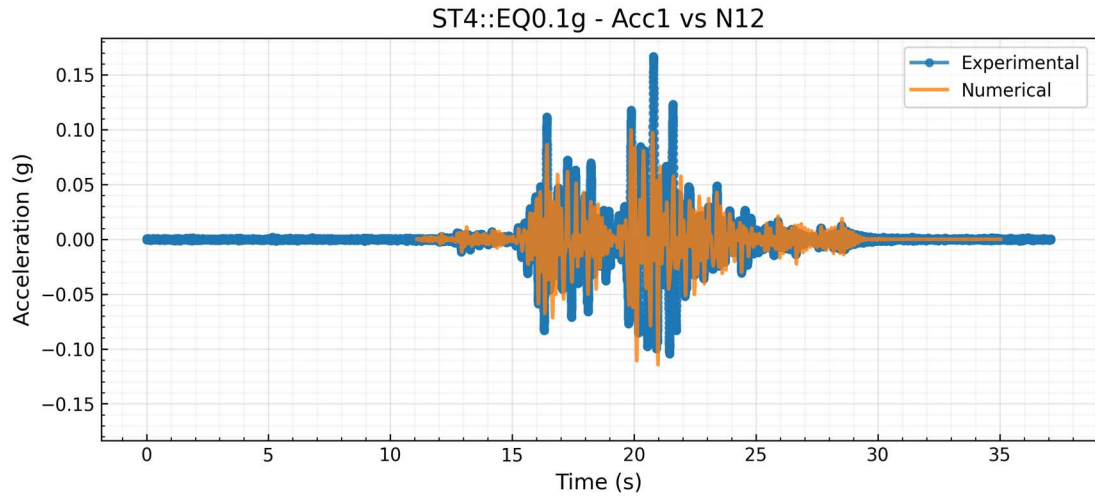


Figure 178 ST4 - Acceleration comparison Acc1 vs N12

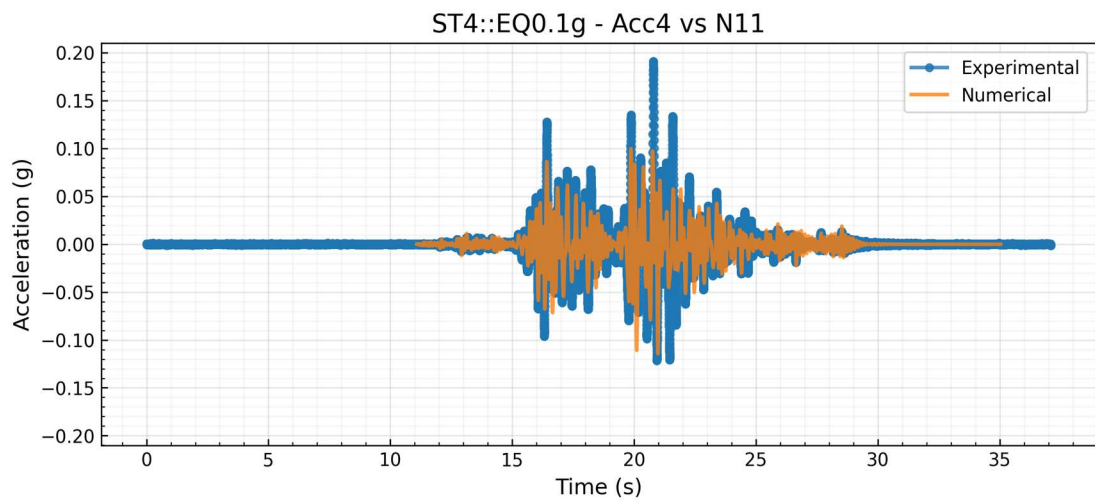


Figure 179 ST4 - Acceleration comparison Acc4 vs N11

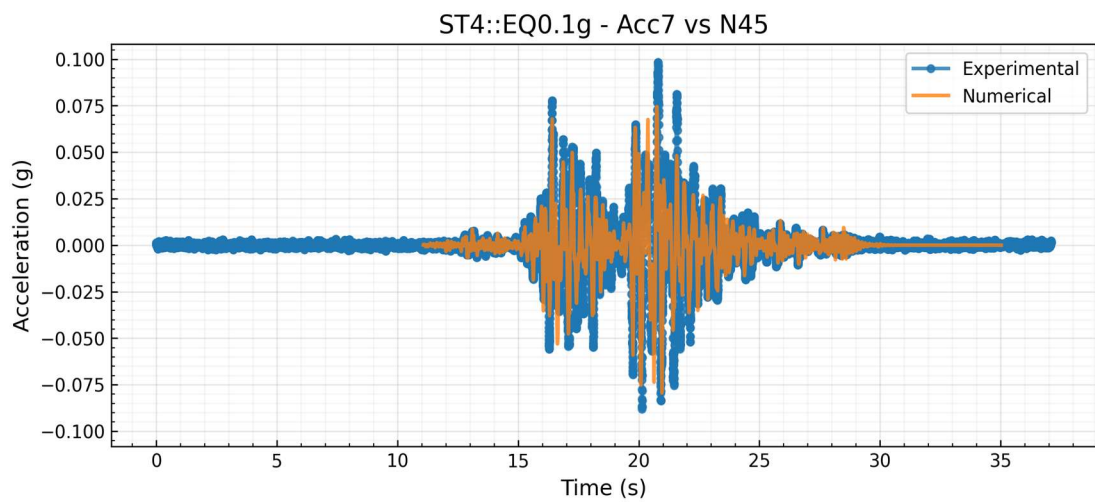


Figure 180 ST4 - Acceleration comparison Acc7 vs N45

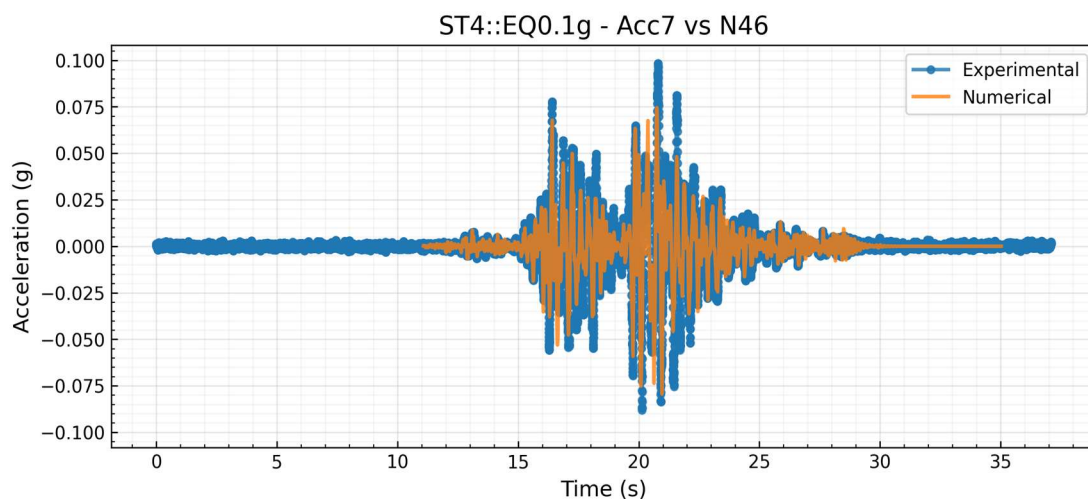


Figure 181 ST4 - Acceleration comparison Acc7 vs N46

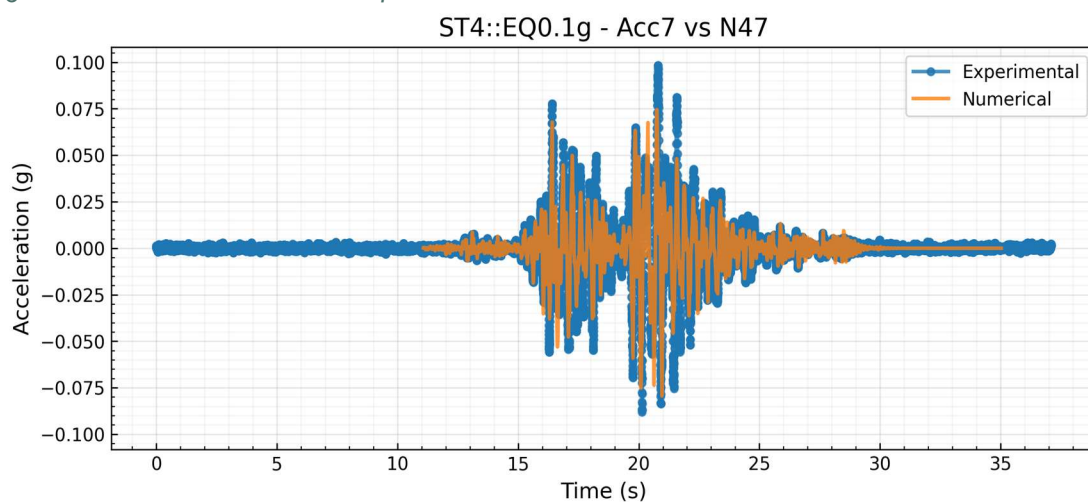


Figure 182 ST4 - Acceleration comparison Acc7 vs N47

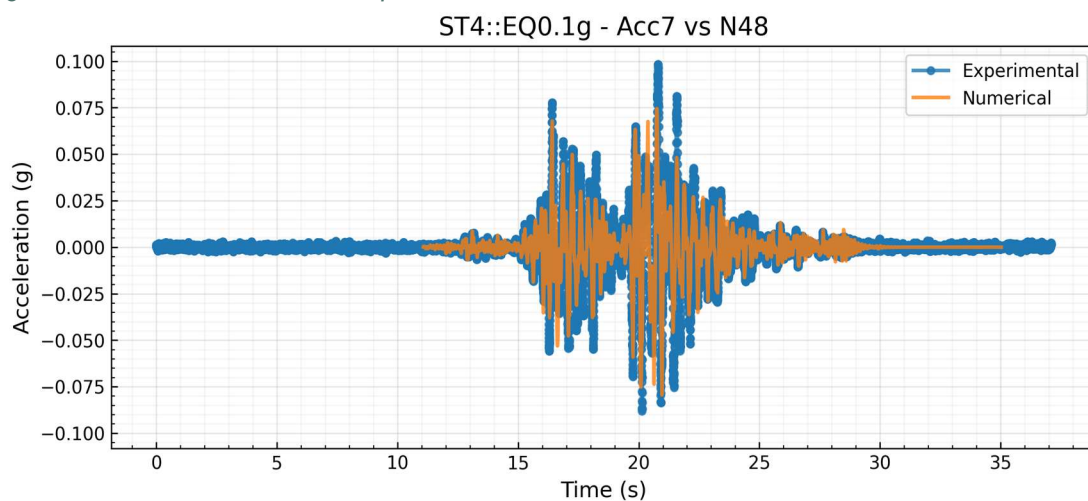


Figure 183 ST4 - Acceleration comparison Acc7 vs N48

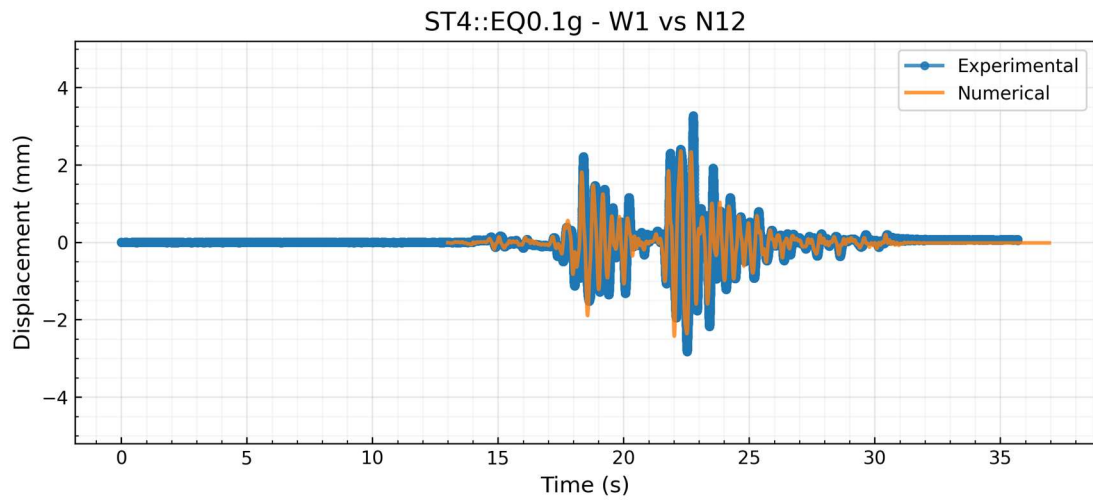


Figure 184 ST4 - Displacement comparison W1 vs N12

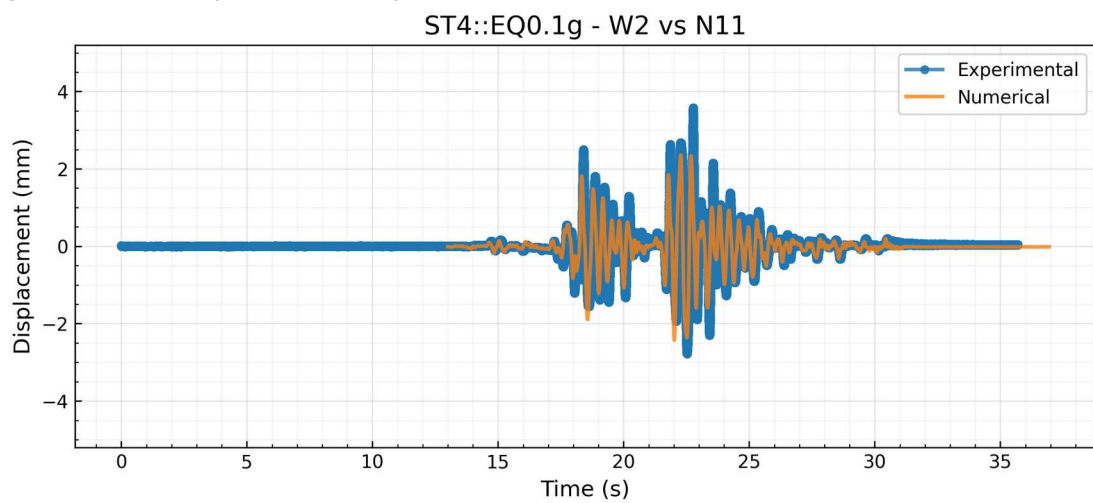


Figure 185 ST4 - Displacement comparison W2 vs N11

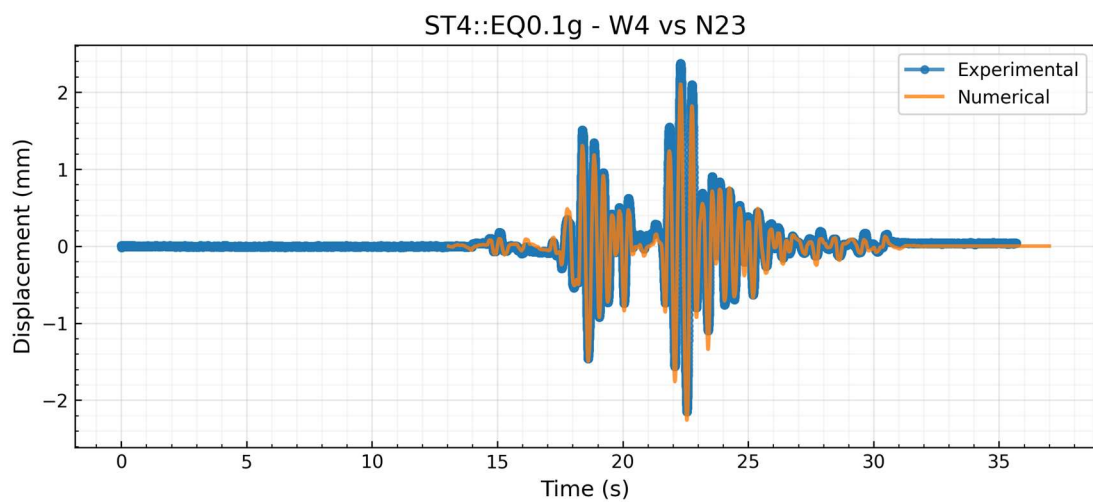


Figure 186 ST4 - Displacement comparison W4 vs N23

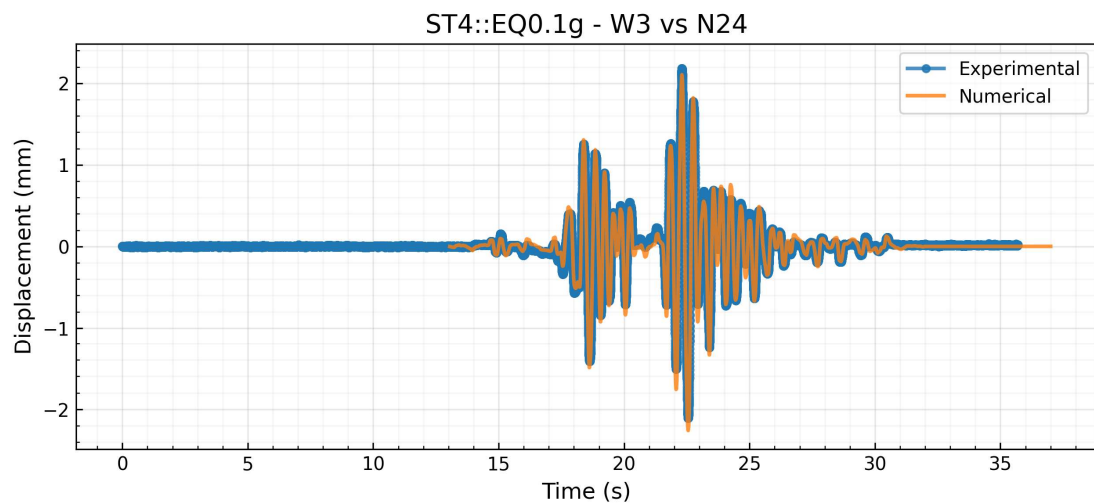


Figure 187 ST4 - Displacement comparison W3 vs N24

6.3 ST6::EQ0.14G RESULTS

The result for draw-wires and accelerometers for ST6::EQ0.14g are presented here.

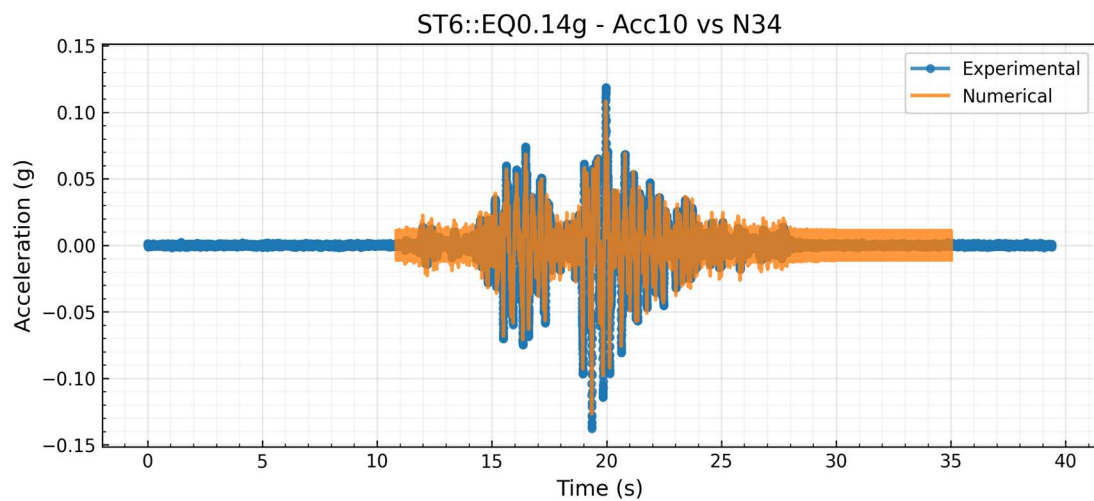


Figure 188 ST6 - Acceleration comparison Acc10 vs N34

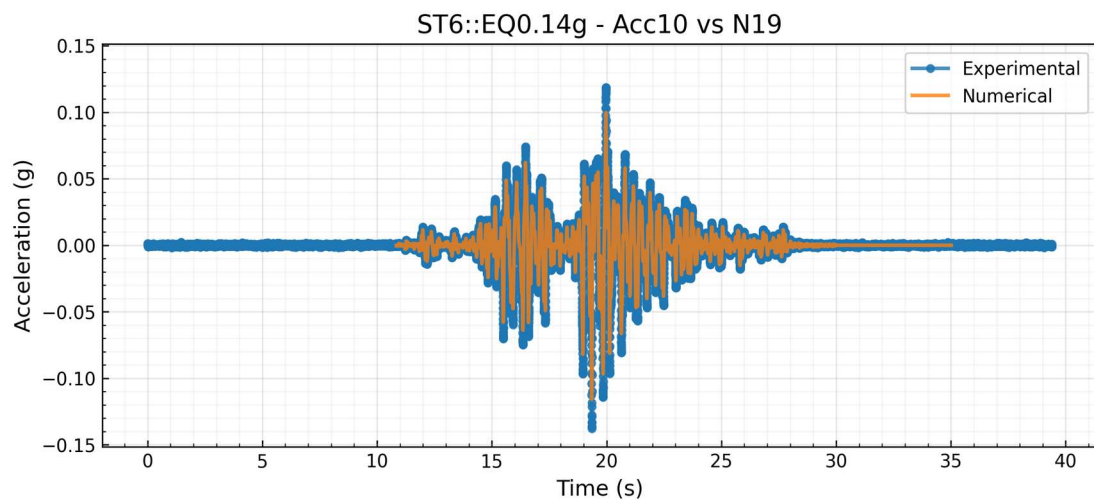


Figure 189 ST6 - Acceleration comparison Acc10 vs N19

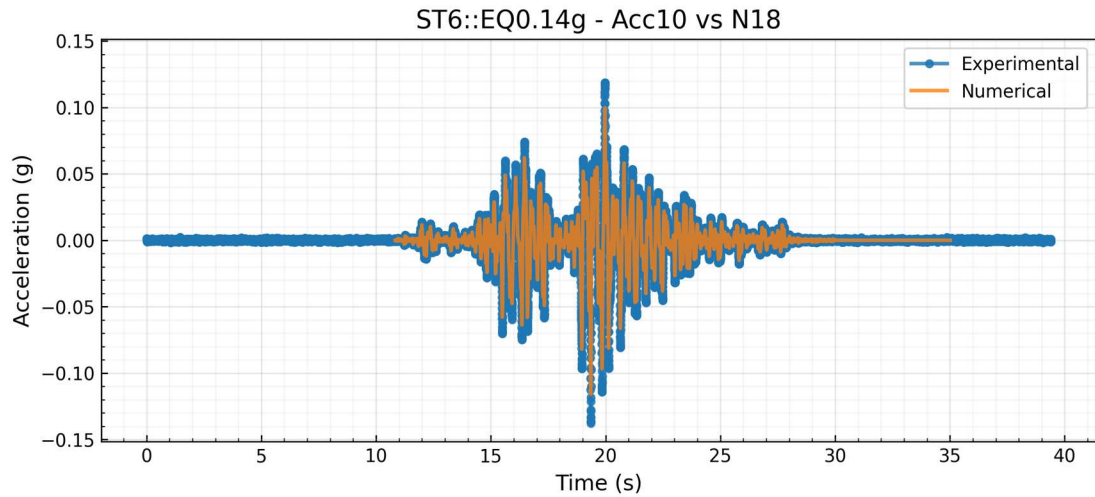


Figure 190 ST6 - Acceleration comparison Acc10 vs N18

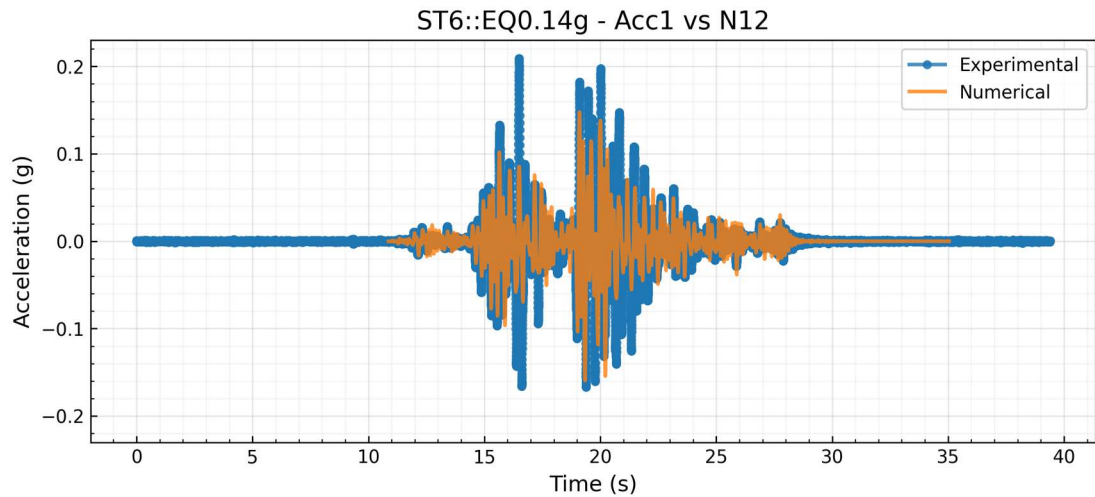


Figure 191 ST6 - Acceleration comparison Acc1 vs N12

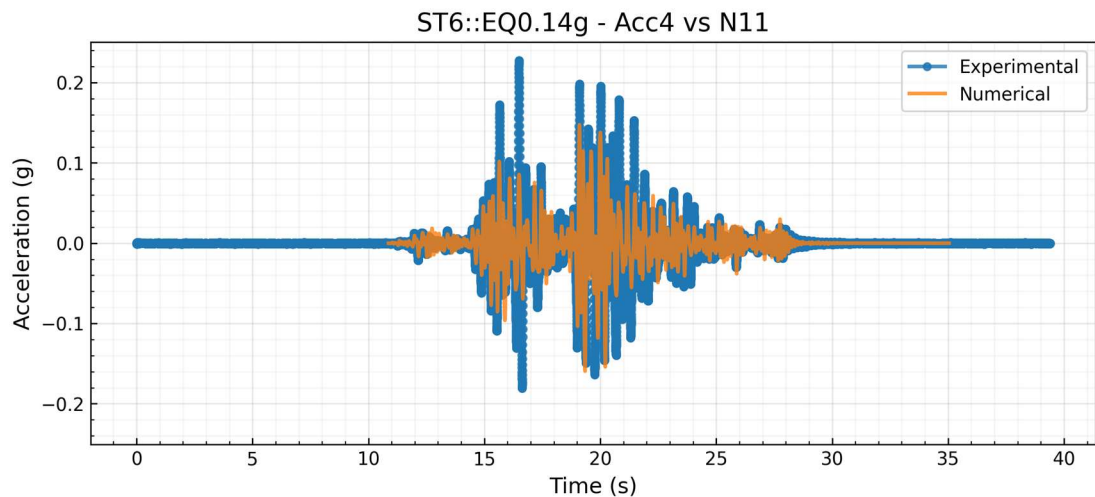


Figure 192 ST6 - Acceleration comparison Acc4 vs N11

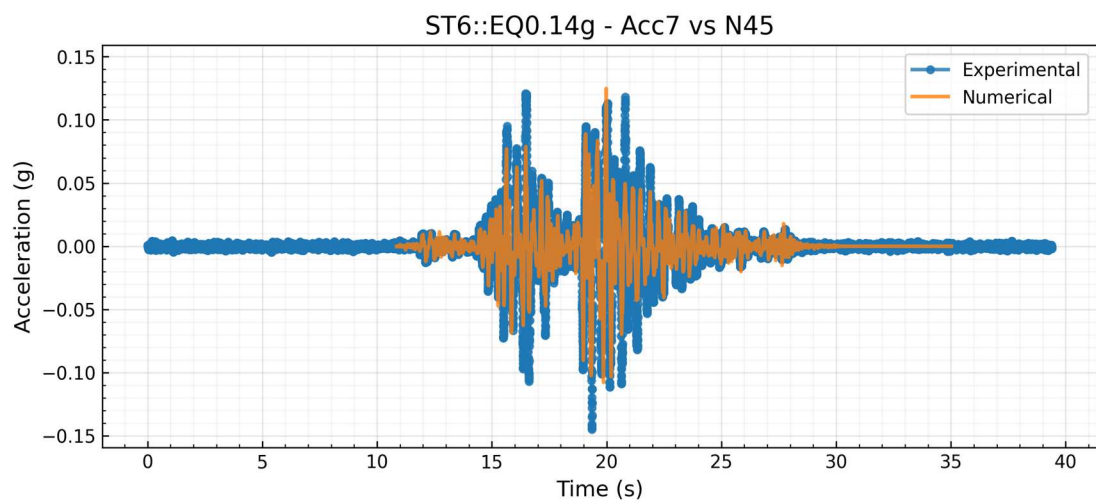


Figure 193 ST6 - Acceleration comparison Acc7 vs N45

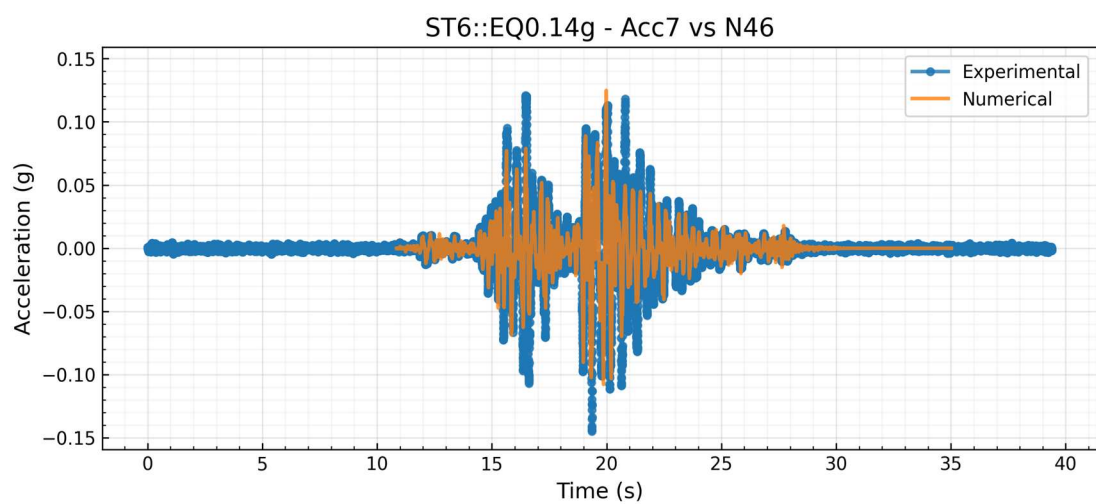


Figure 194 ST6 - Acceleration comparison Acc7 vs N46

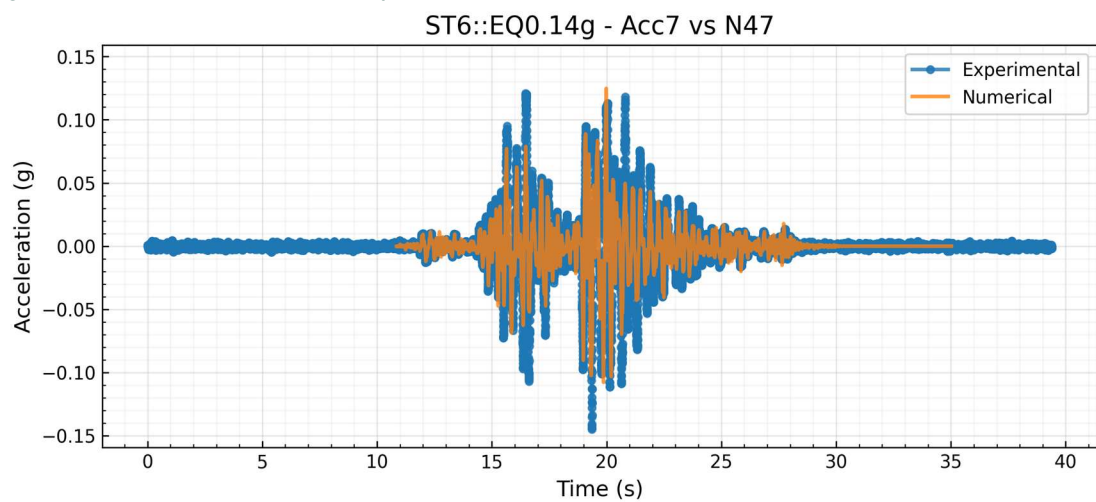


Figure 195 ST6 - Acceleration comparison Acc7 vs N47

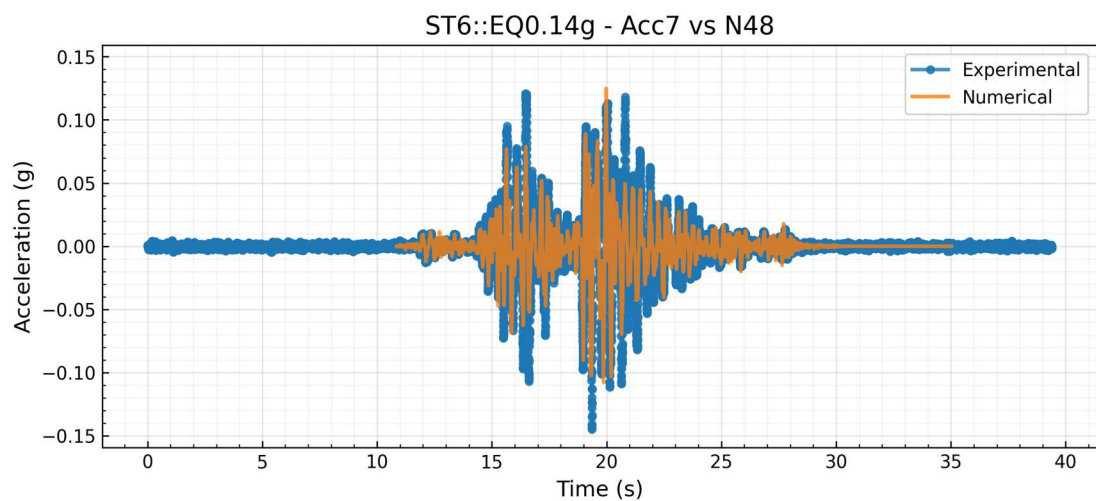


Figure 196 ST6 - Acceleration comparison Acc7 vs N48

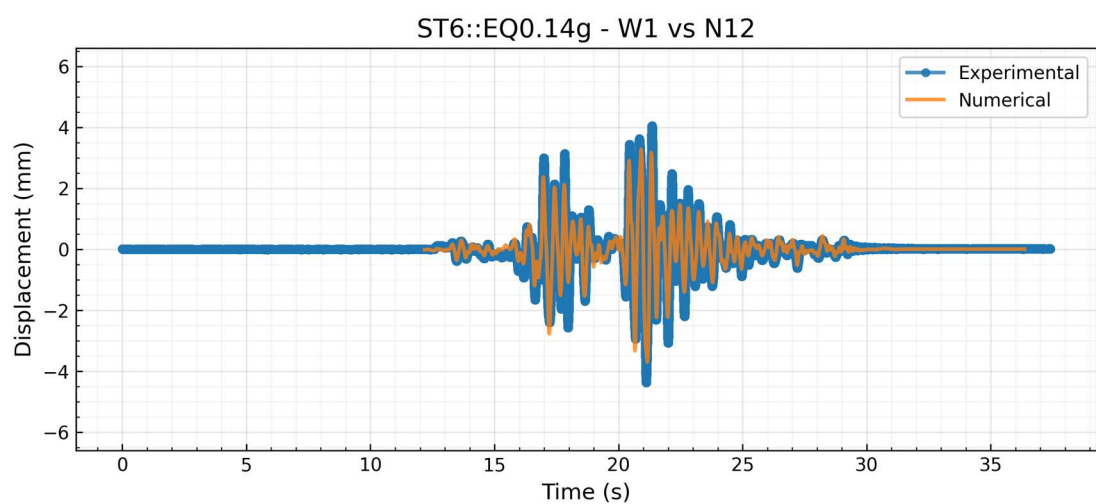


Figure 197 ST6 - Displacement comparison W1 vs N12

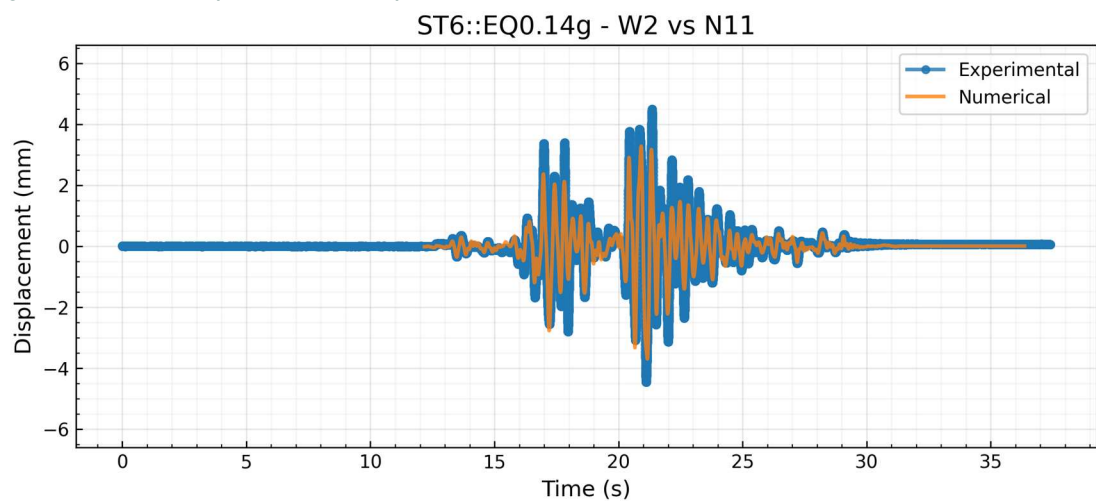


Figure 198 ST6 - Displacement comparison W2 vs N11

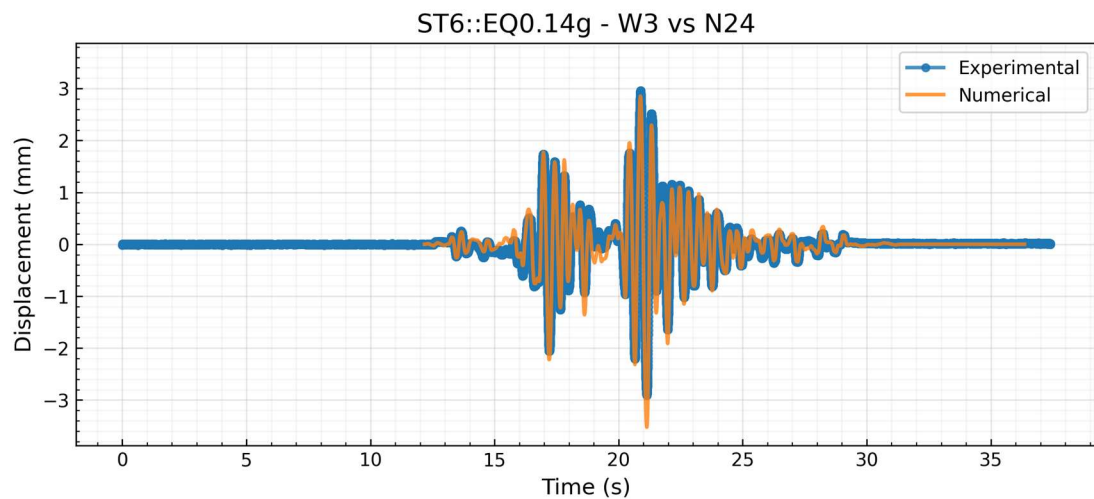


Figure 199 ST6 - Displacement comparison W3 vs N24

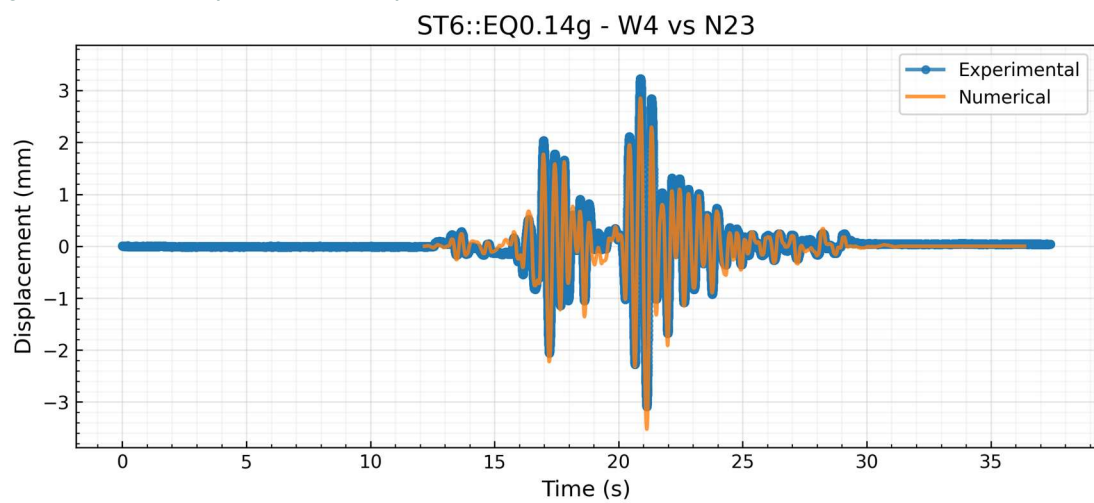


Figure 200 ST6 - Displacement comparison W4 vs N23

6.4 ST7::EQ0.2G RESULTS

The result for draw-wires and accelerometers for ST7::EQ0.2g are presented here.

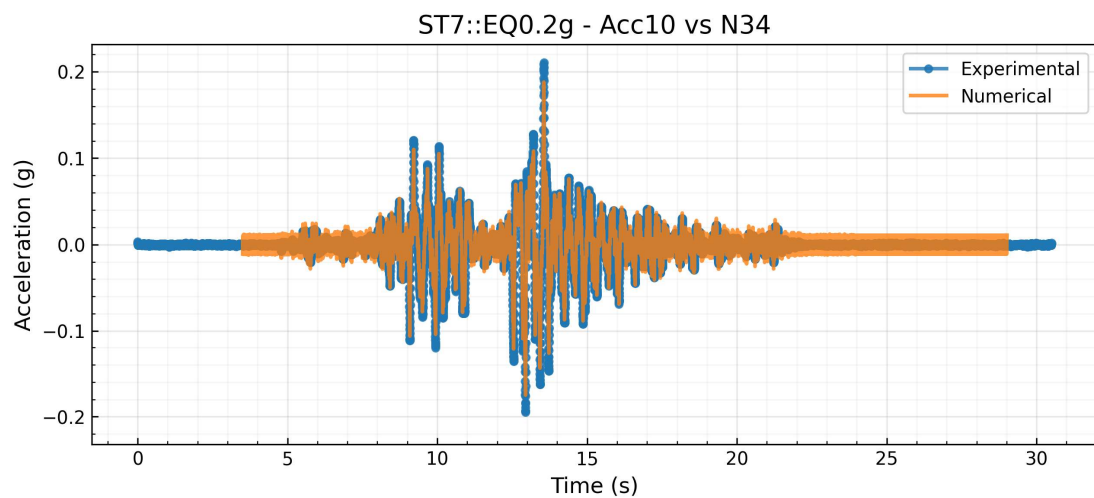


Figure 201 ST7 - Acceleration comparison Acc10 vs N34

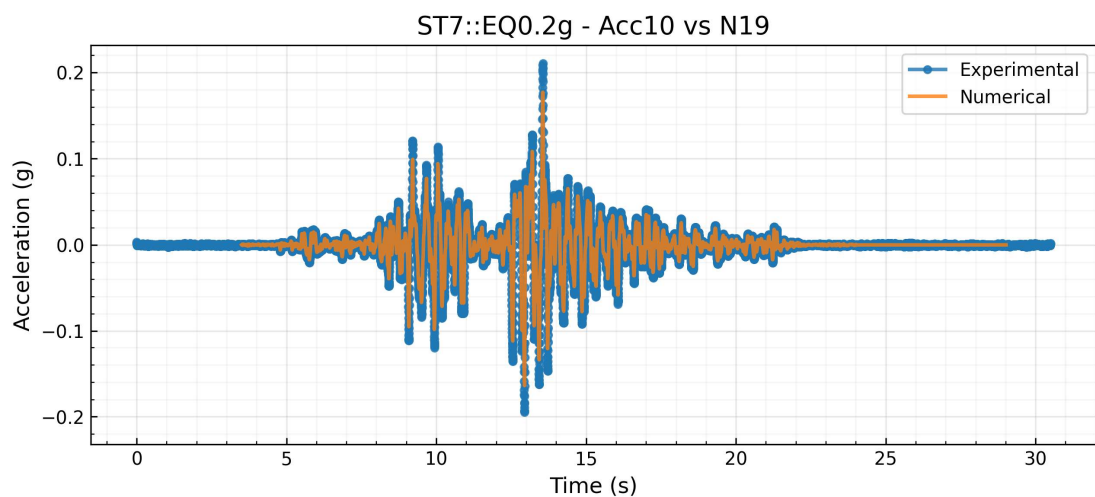


Figure 202 ST7 - Acceleration comparison Acc10 vs N19

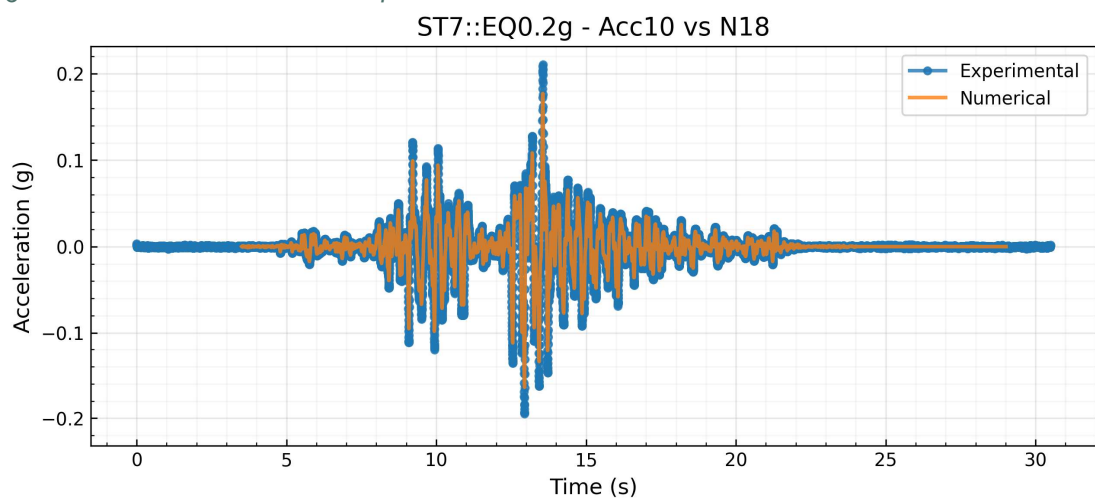


Figure 203 ST7 - Acceleration comparison Acc10 vs N18

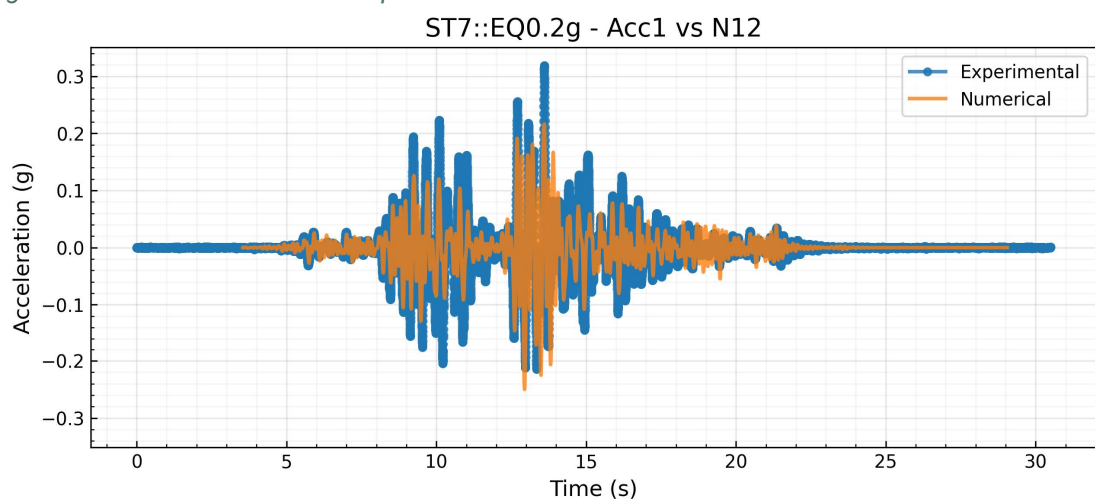


Figure 204 ST7 - Acceleration comparison Acc1 vs N12

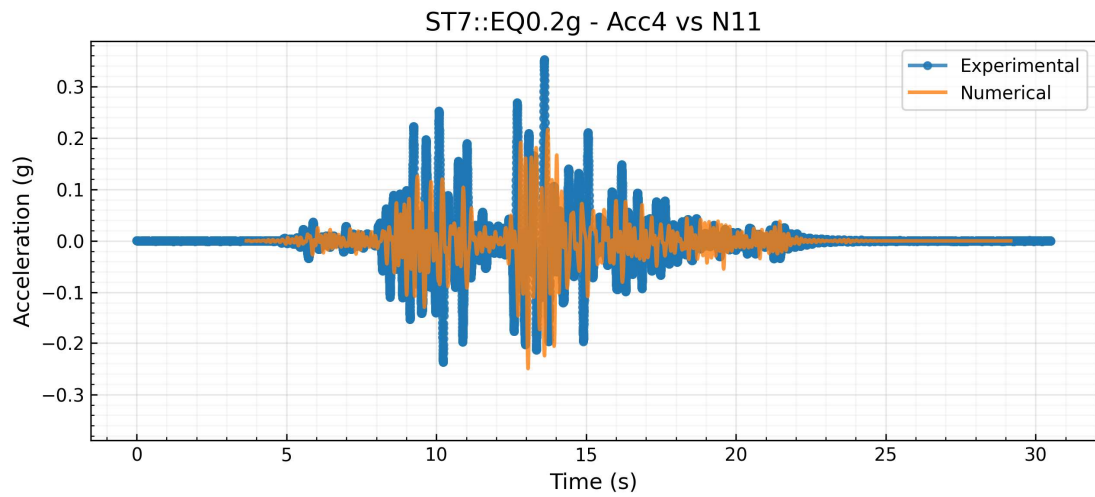


Figure 205 ST7 - Acceleration comparison Acc4 vs N11

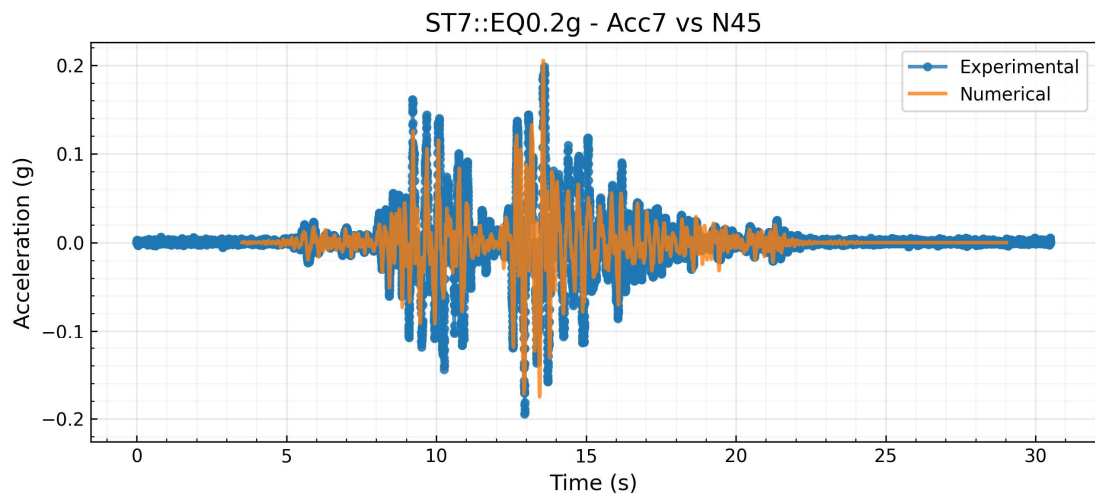


Figure 206 ST7 - Acceleration comparison Acc7 vs N45

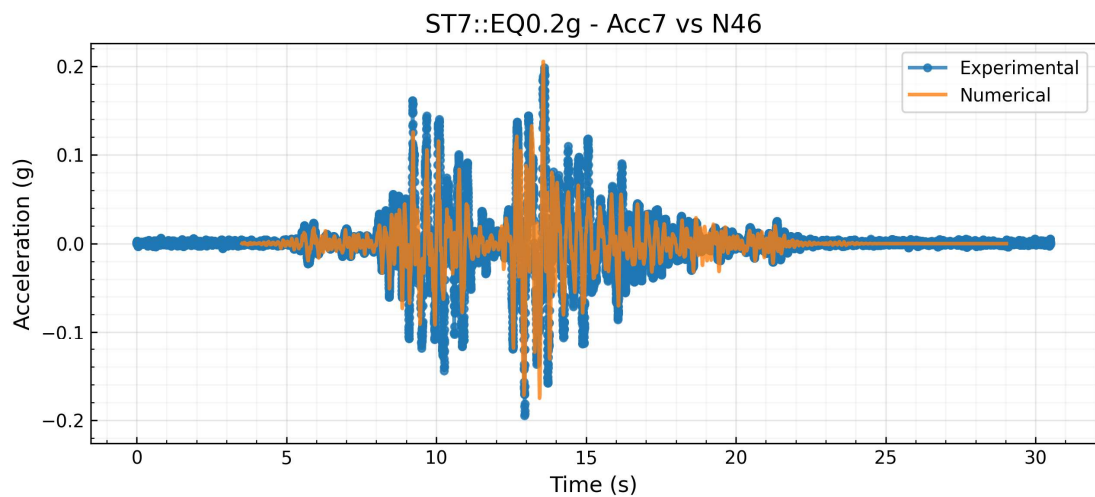


Figure 207 ST7 - Acceleration comparison Acc7 vs N46

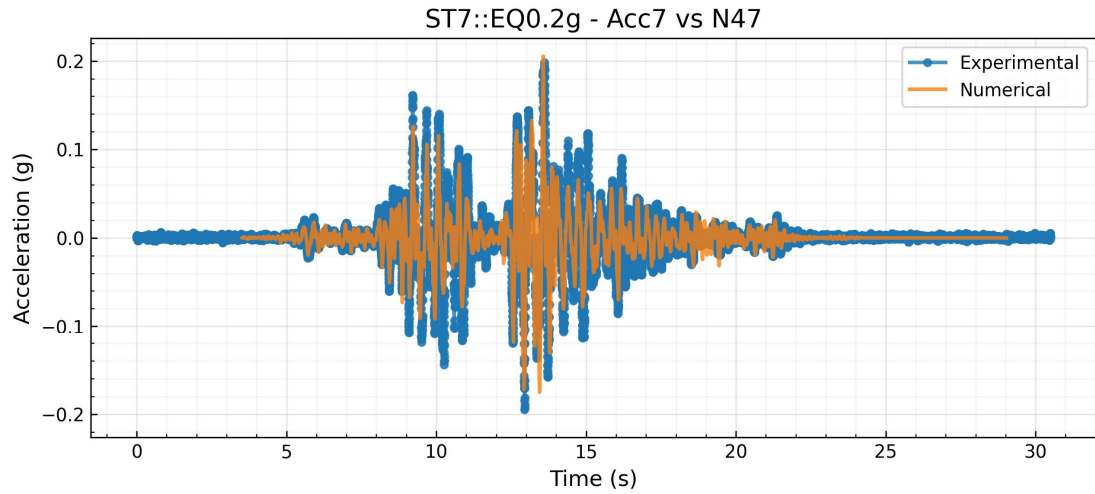


Figure 208 ST7 - Acceleration comparison Acc7 vs N47

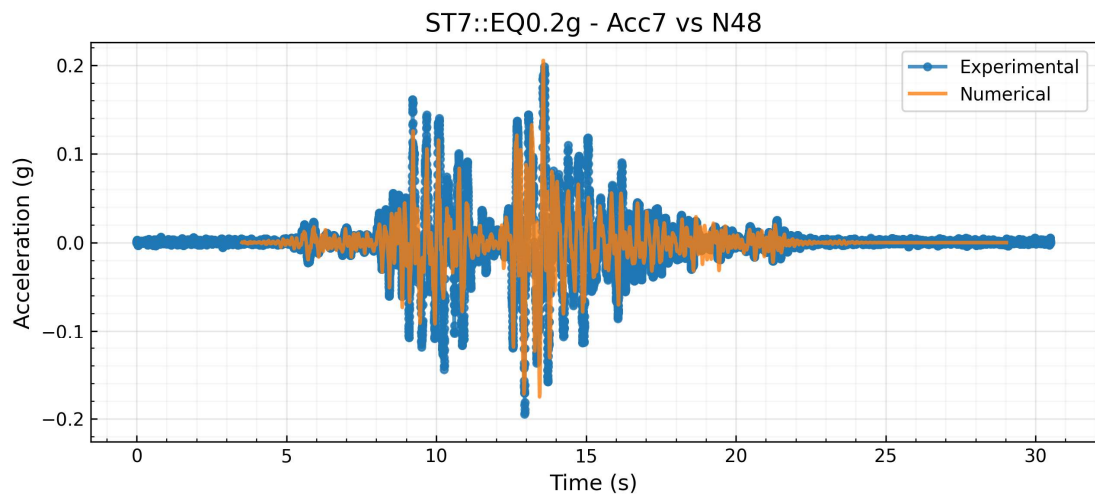


Figure 209 ST7 - Acceleration comparison Acc7 vs N48

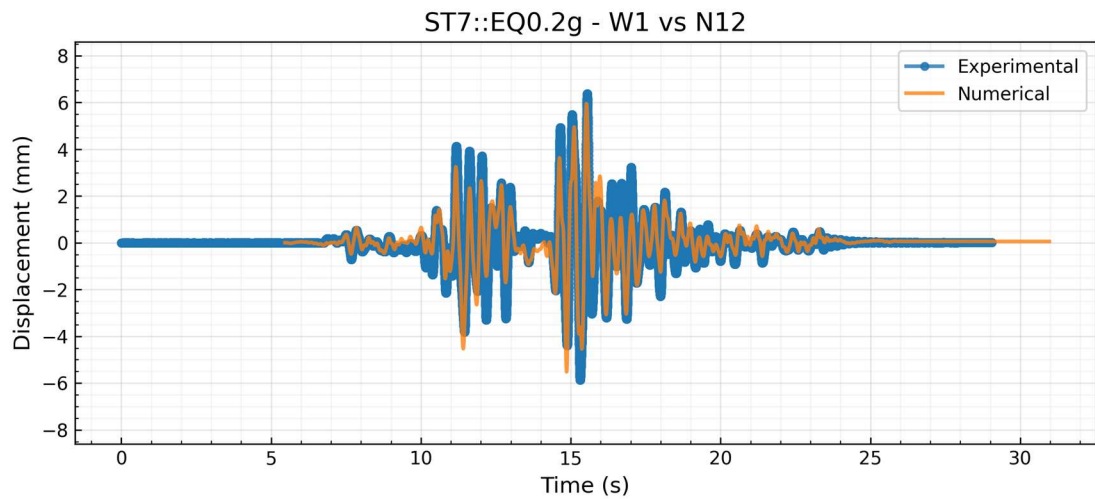


Figure 210 ST7 - Displacement comparison W1 vs N12

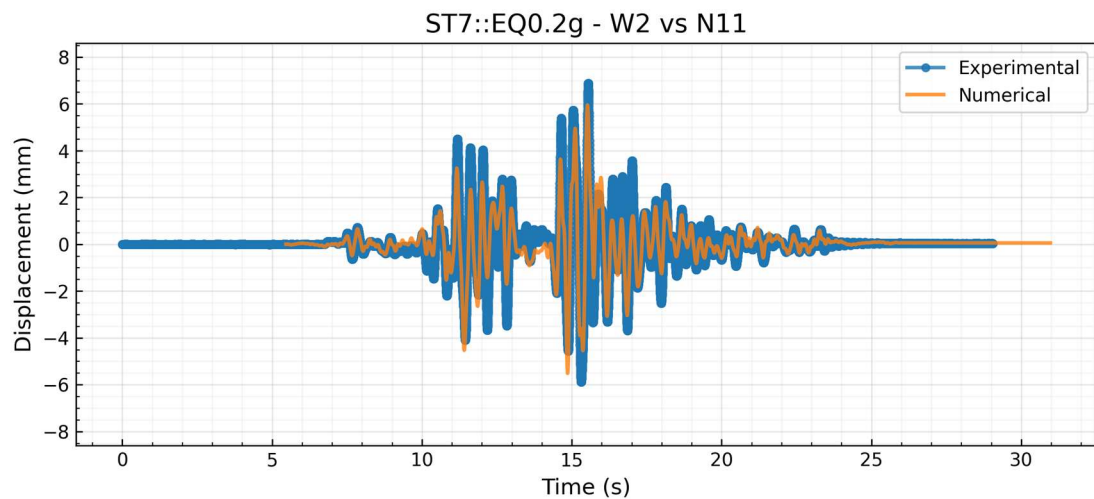


Figure 211 ST7 - Displacement comparison W2 vs N11

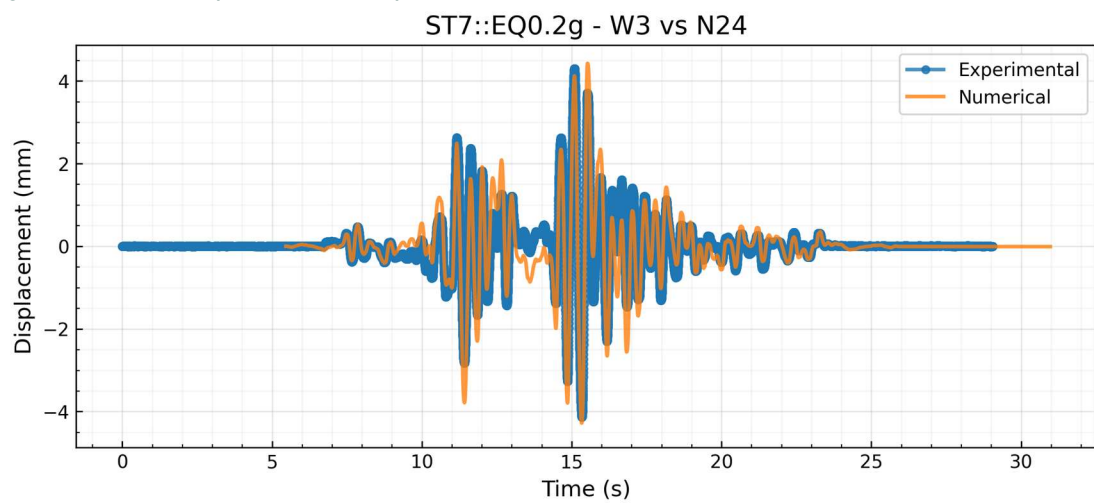


Figure 212 ST7 - Displacement comparison W3 vs N24

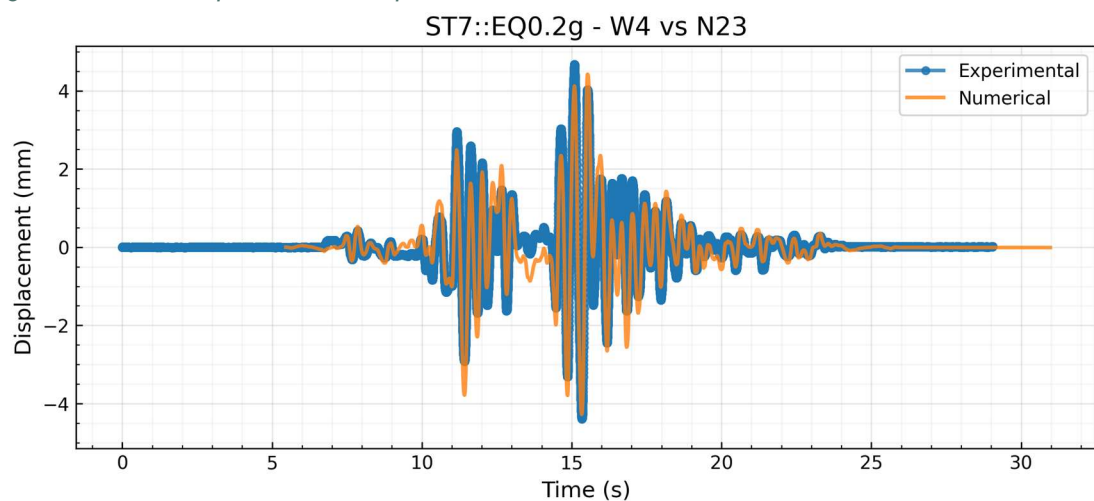


Figure 213 ST7 - Displacement comparison W4 vs N23

6.5 ST9::EQ0.34G RESULTS

The result for draw-wires and accelerometers for ST9::EQ0.34g are presented here.

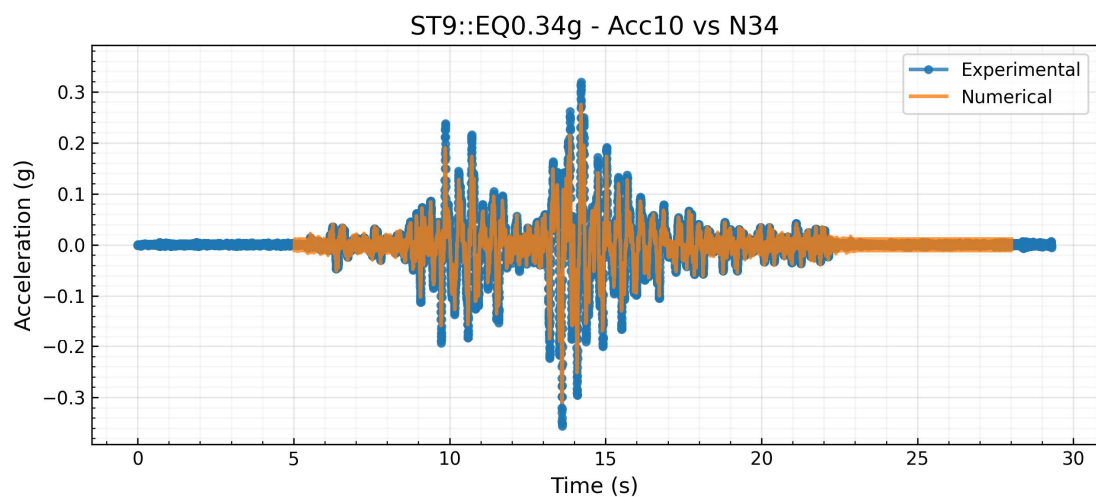


Figure 214 ST9 - Acceleration comparison Acc10 vs N34

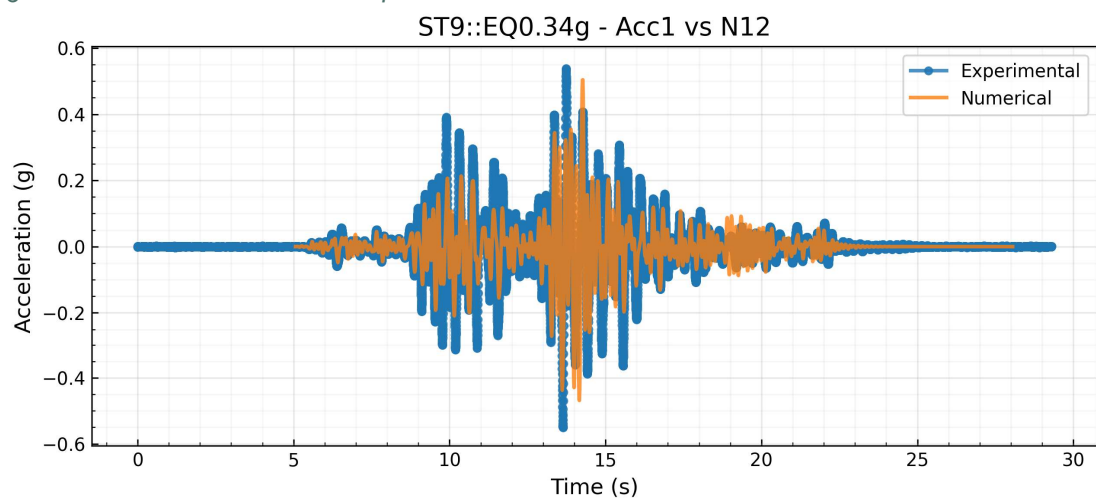


Figure 215 ST9 - Acceleration comparison Acc1 vs N12

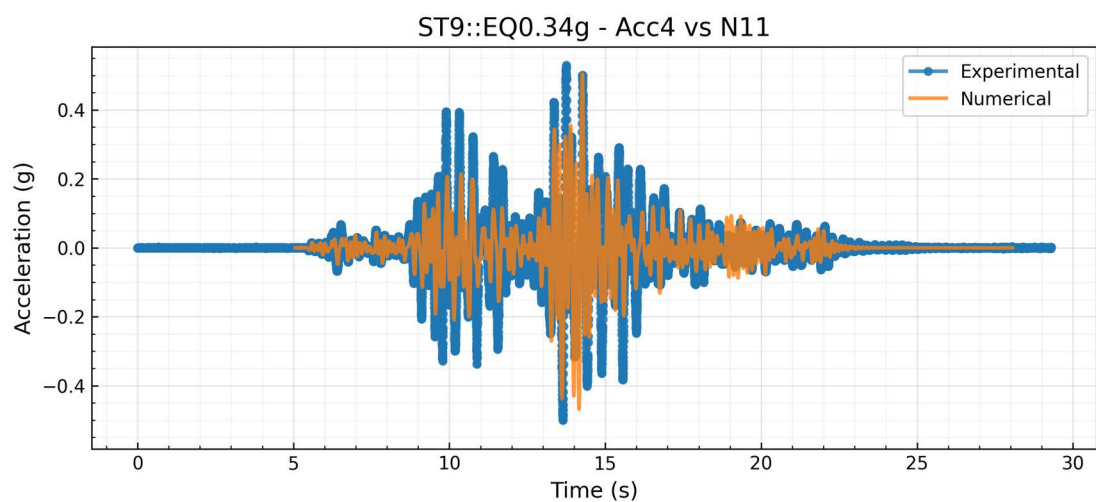


Figure 216 ST9 - Acceleration comparison Acc4 vs N11

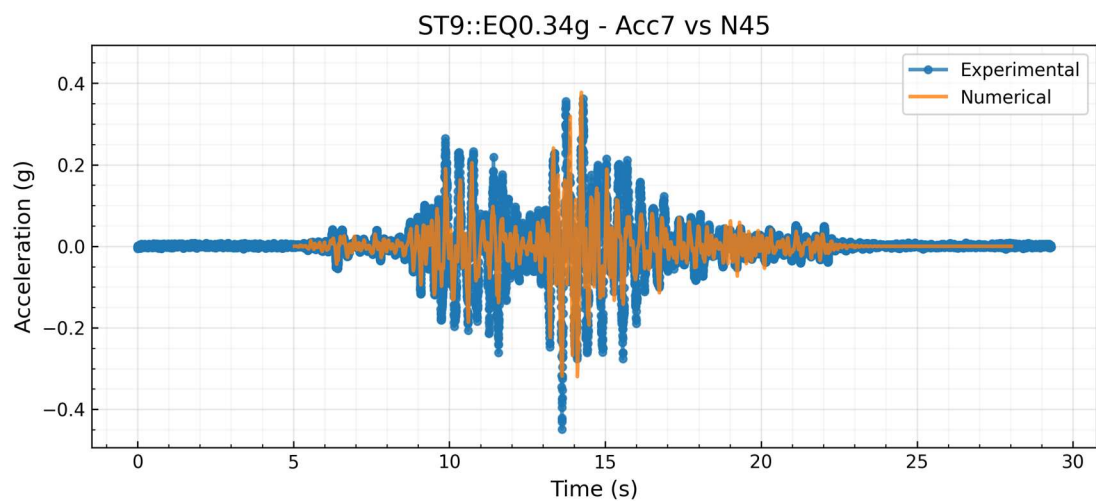


Figure 217 ST9 - Acceleration comparison Acc7 vs N45

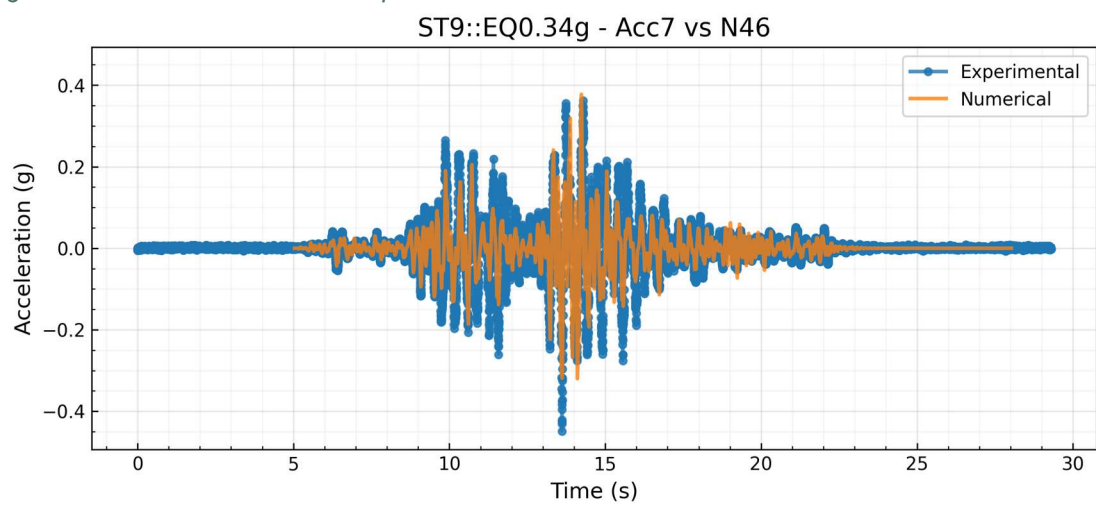


Figure 218 ST9 - Acceleration comparison Acc7 vs N46

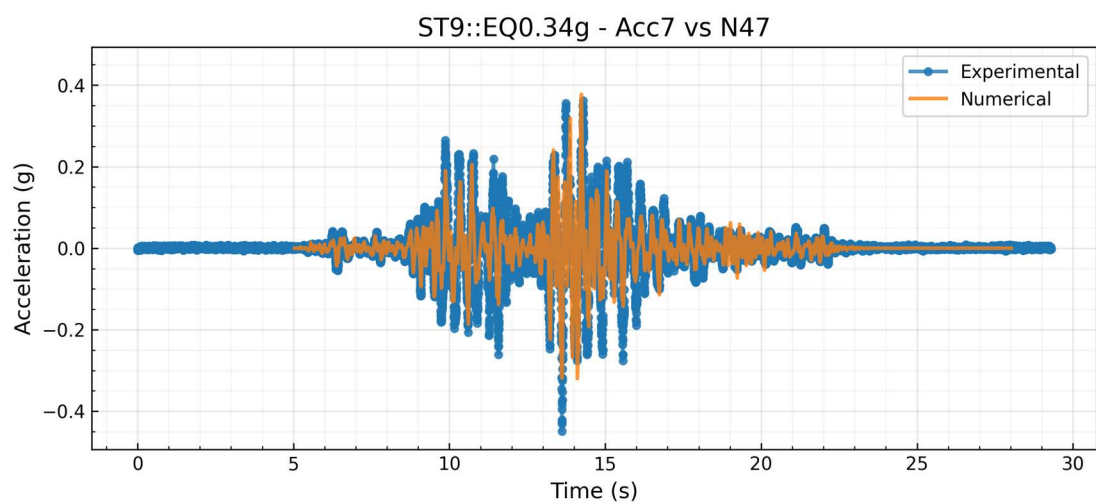


Figure 219 ST9 - Acceleration comparison Acc7 vs N47

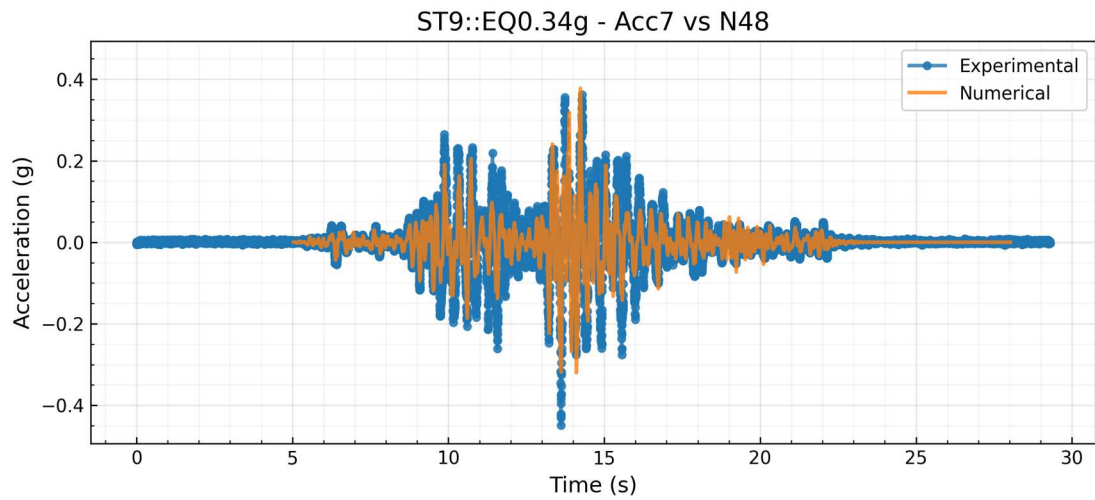


Figure 220 ST9 - Acceleration comparison Acc7 vs N48

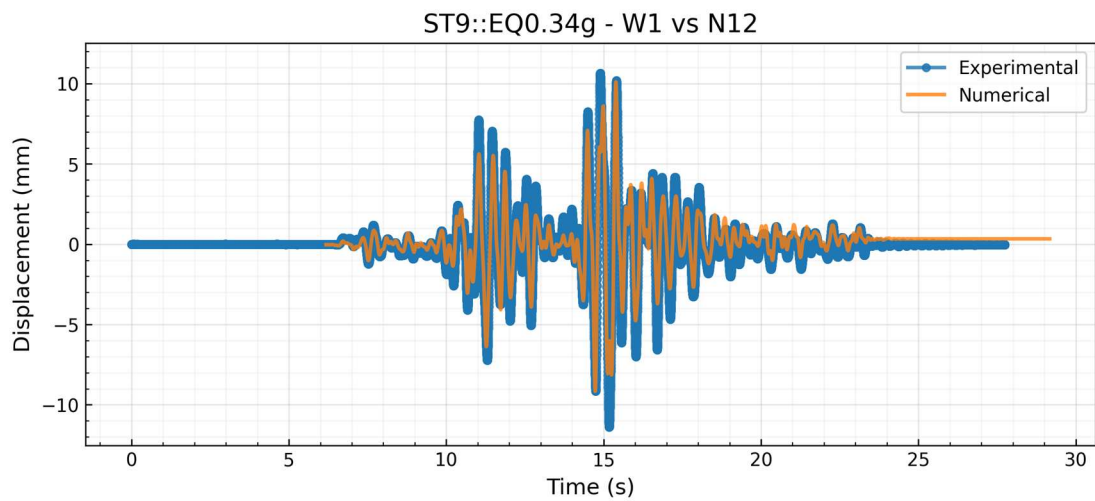


Figure 221 ST9 - Displacement comparison W1 vs N12

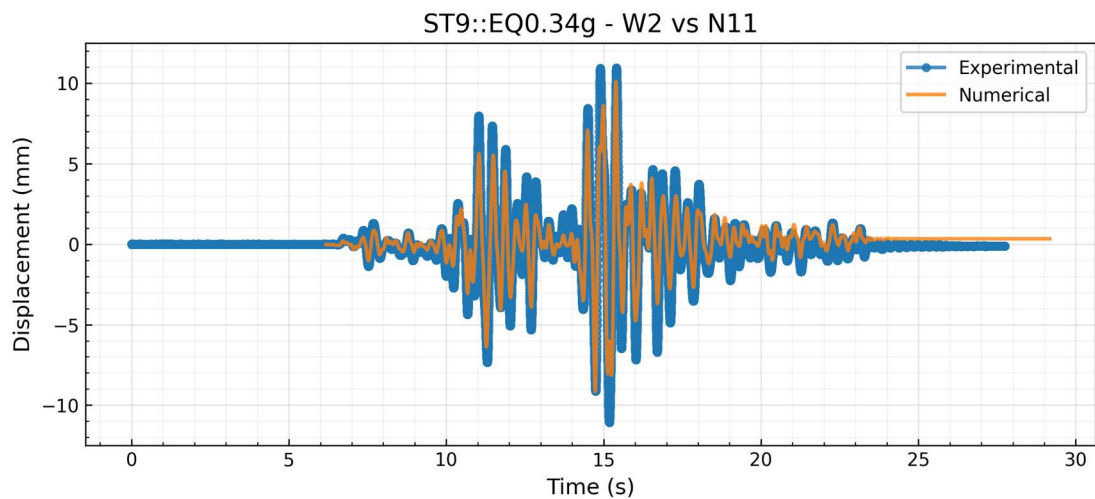


Figure 222 ST9 - Displacement comparison W2 vs N11

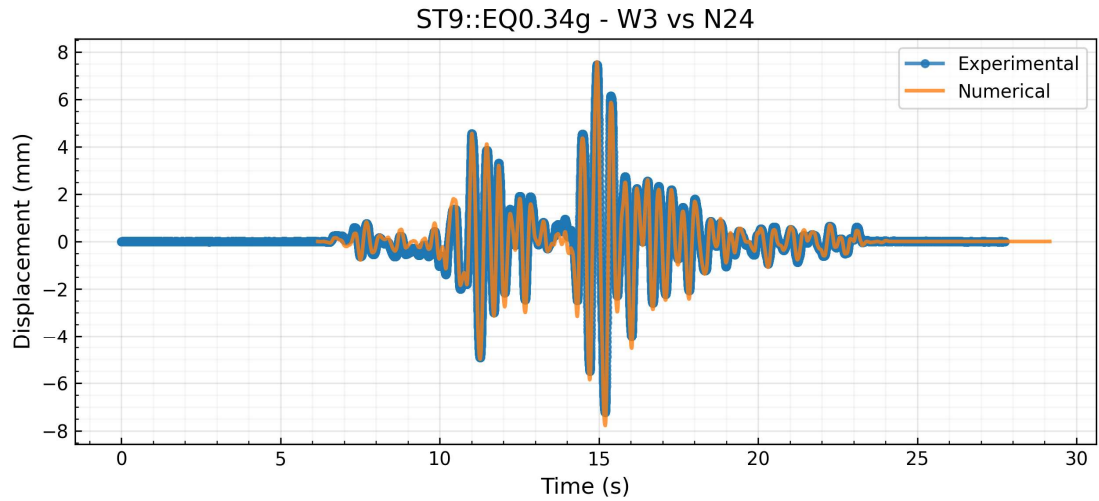


Figure 223 ST9 - Displacement comparison W3 vs N24

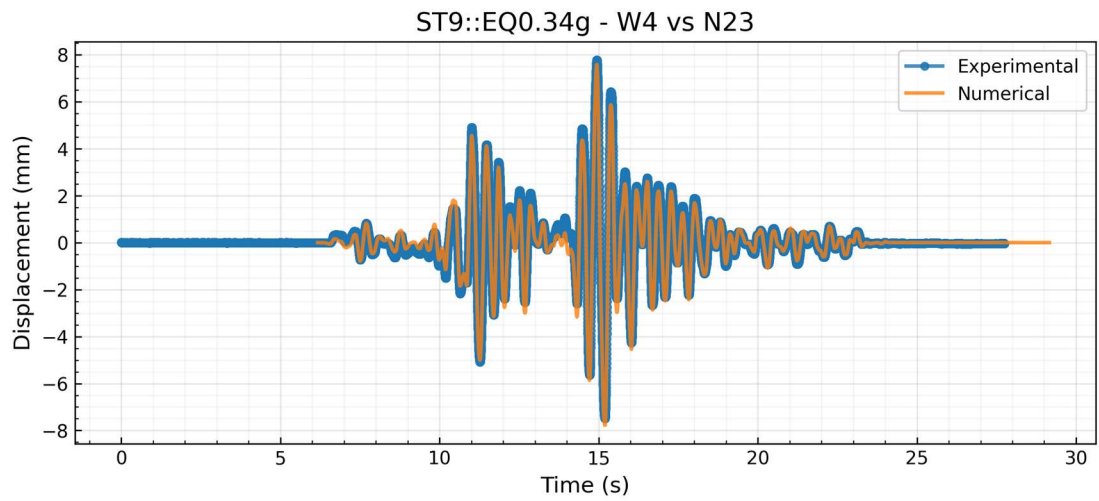


Figure 224 ST9 - Displacement comparison W4 vs N23

6.6 ST11::EQ0.5G RESULTS

The result for draw-wires and accelerometers for ST11::EQ0.5g are presented here.

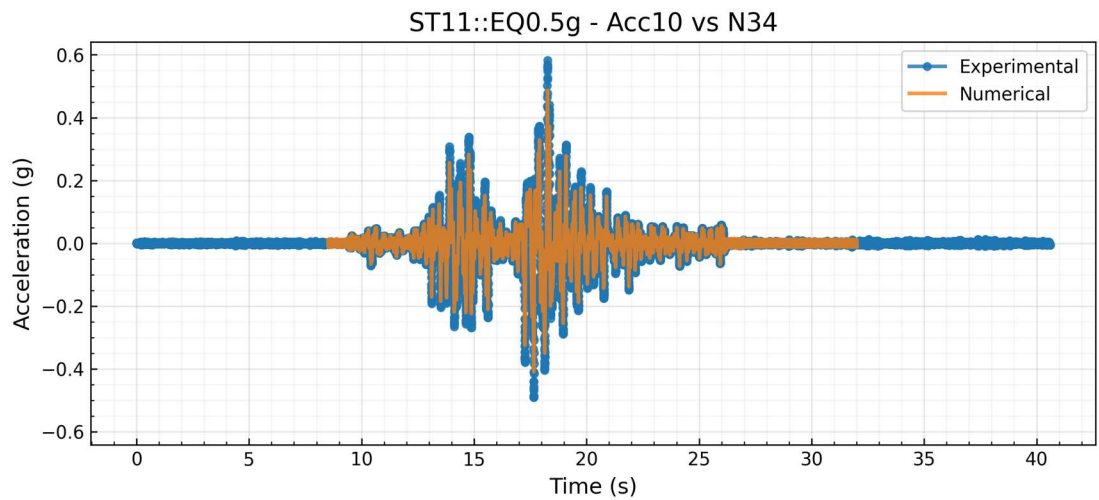


Figure 225 ST11 - Acceleration comparison Acc10 vs N34

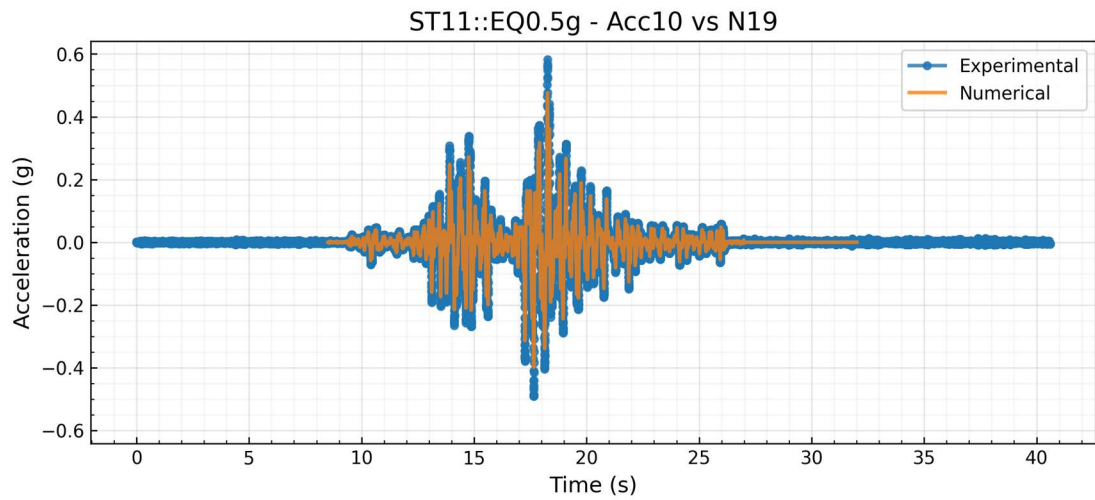


Figure 226 ST11 - Acceleration comparison Acc10 vs N19

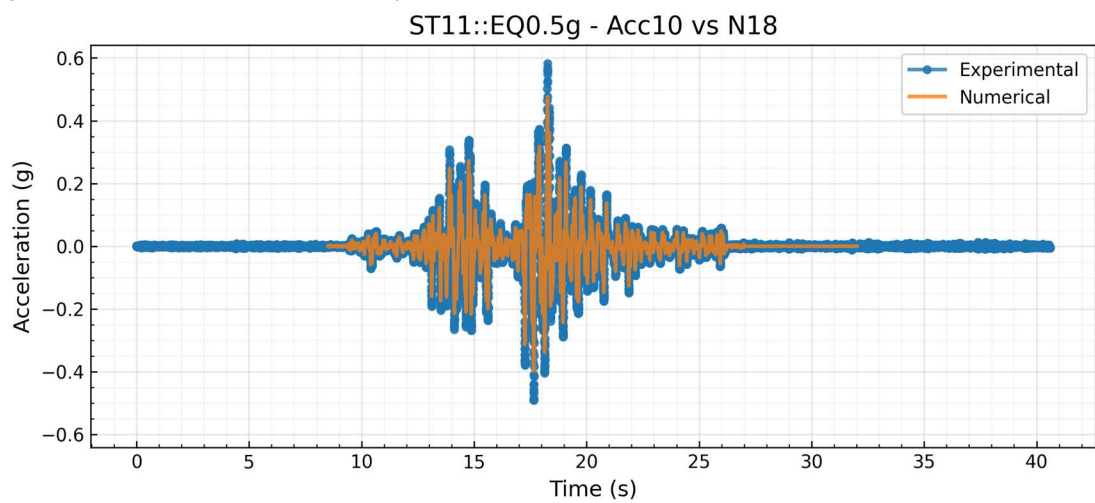


Figure 227 ST11 - Acceleration comparison Acc10 vs N18

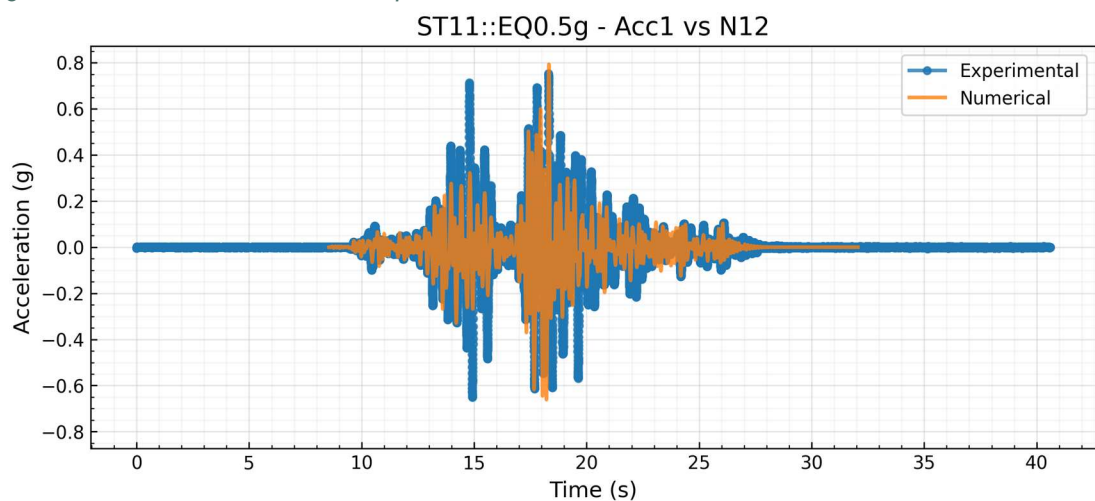


Figure 228 ST11 - Acceleration comparison Acc1 vs N12

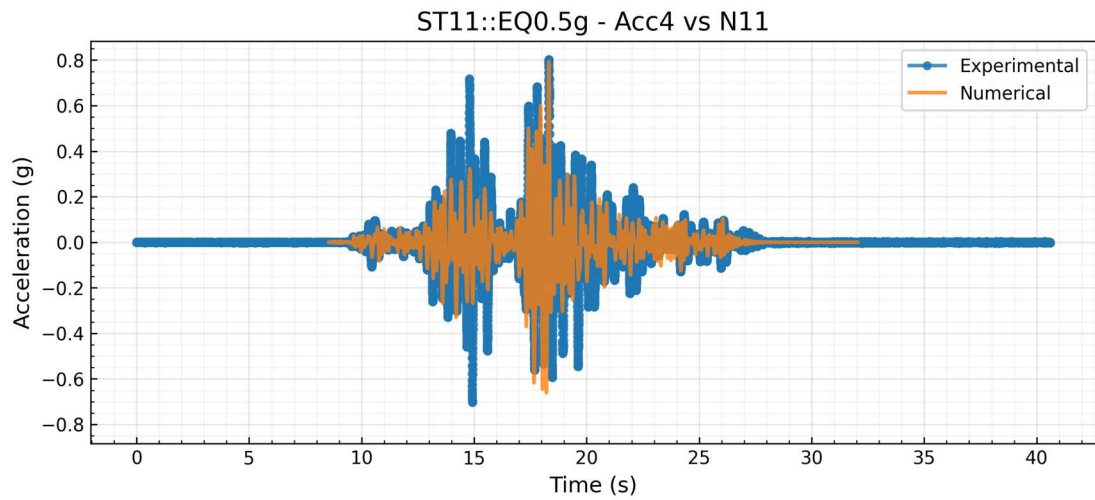


Figure 229 ST11 - Acceleration comparison Acc4 vs N11

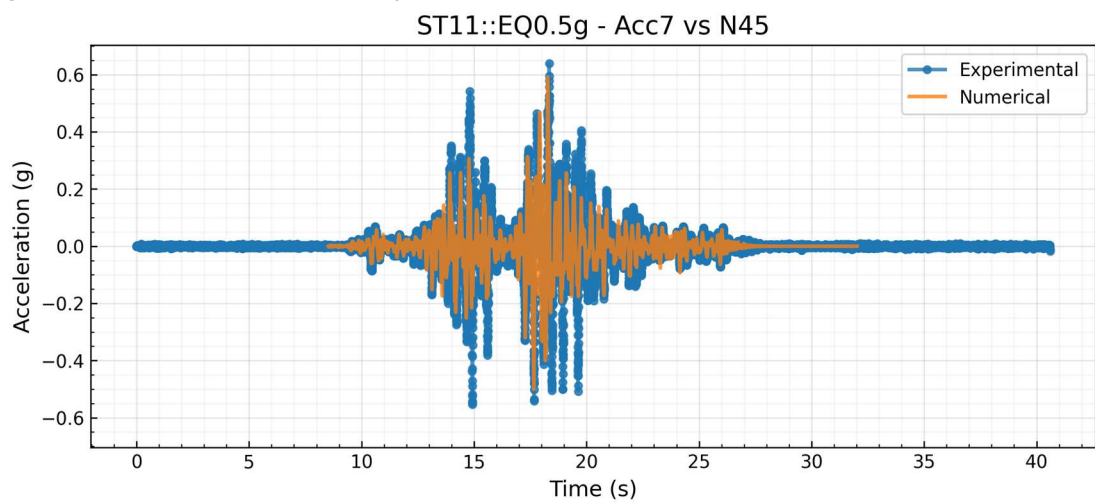


Figure 230 ST11 - Acceleration comparison Acc7 vs N45

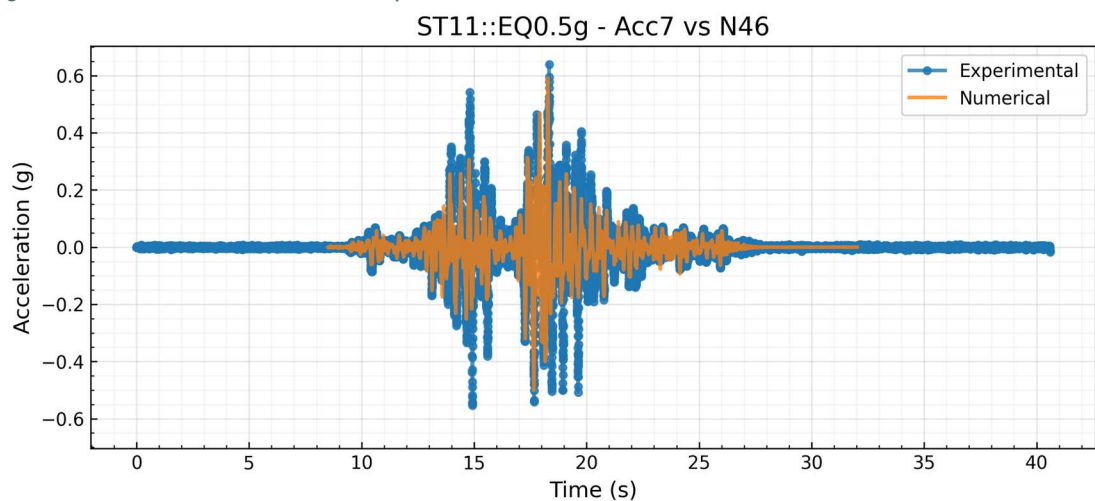


Figure 231 ST11 - Acceleration comparison Acc7 vs N46

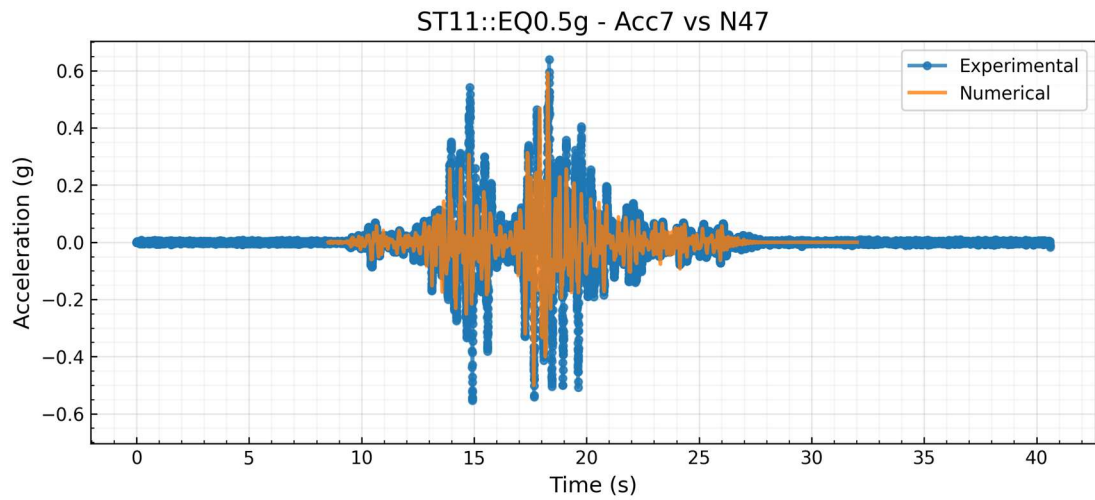


Figure 232 ST11 - Acceleration comparison Acc7 vs N47

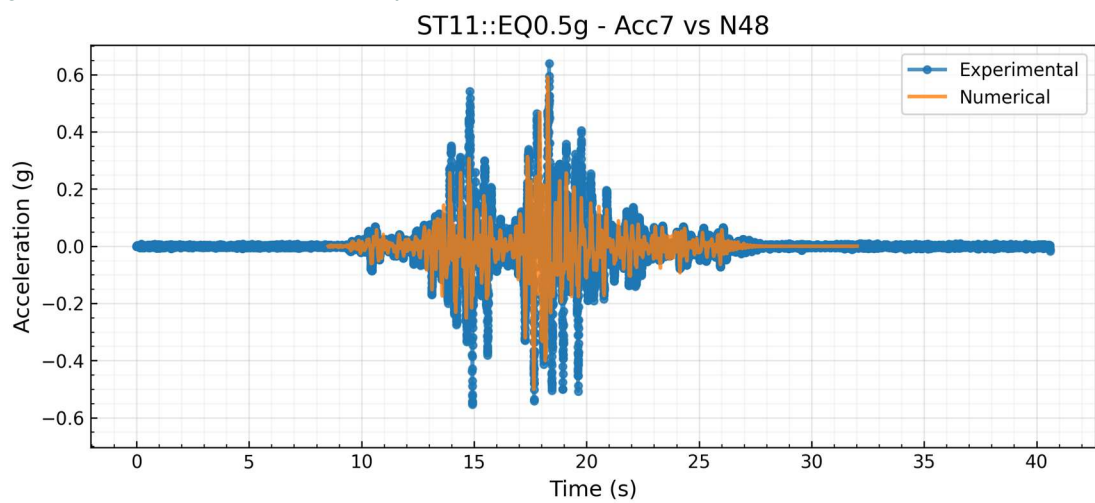


Figure 233 ST11 - Acceleration comparison Acc7 vs N48

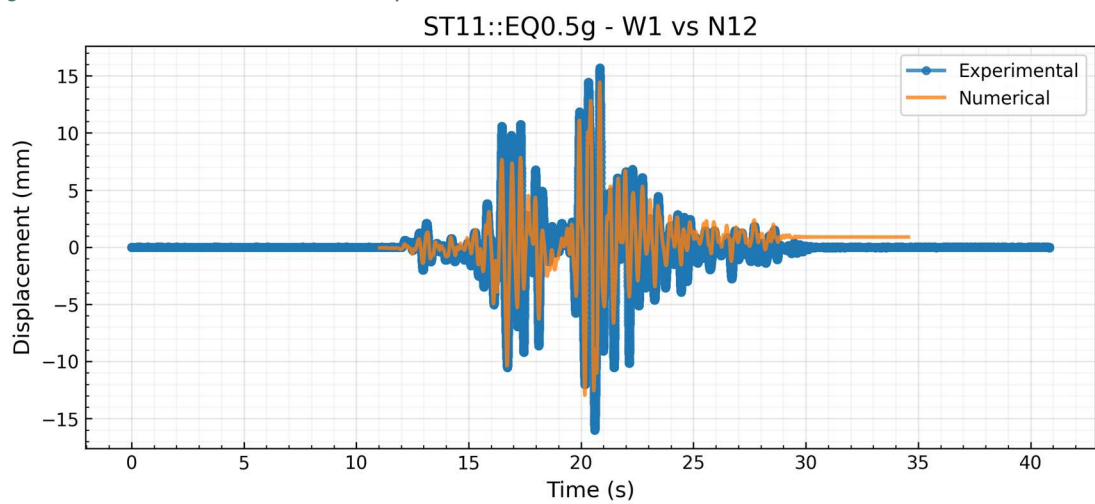


Figure 234 ST11 - Displacement comparison W1 vs N12

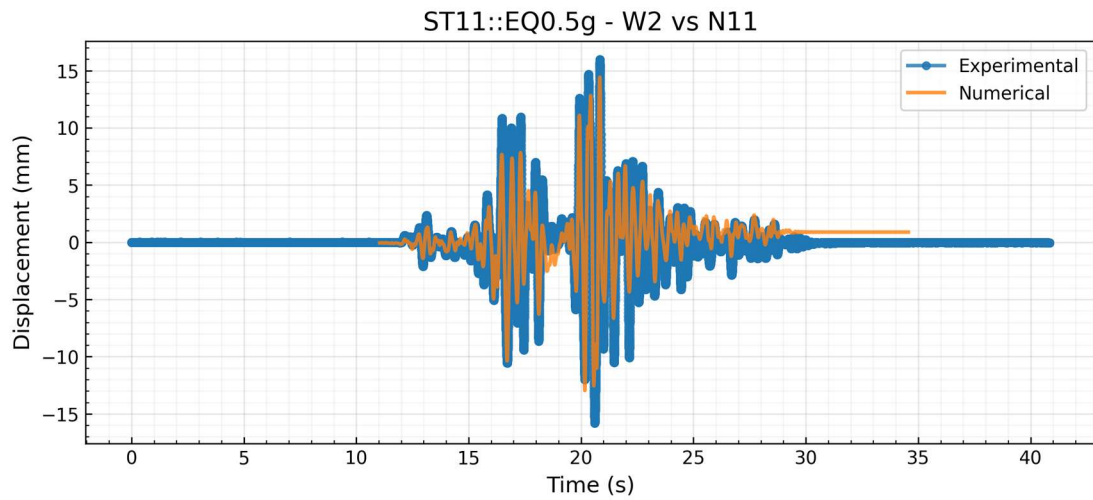


Figure 235 ST11 - Displacement comparison W2 vs N11

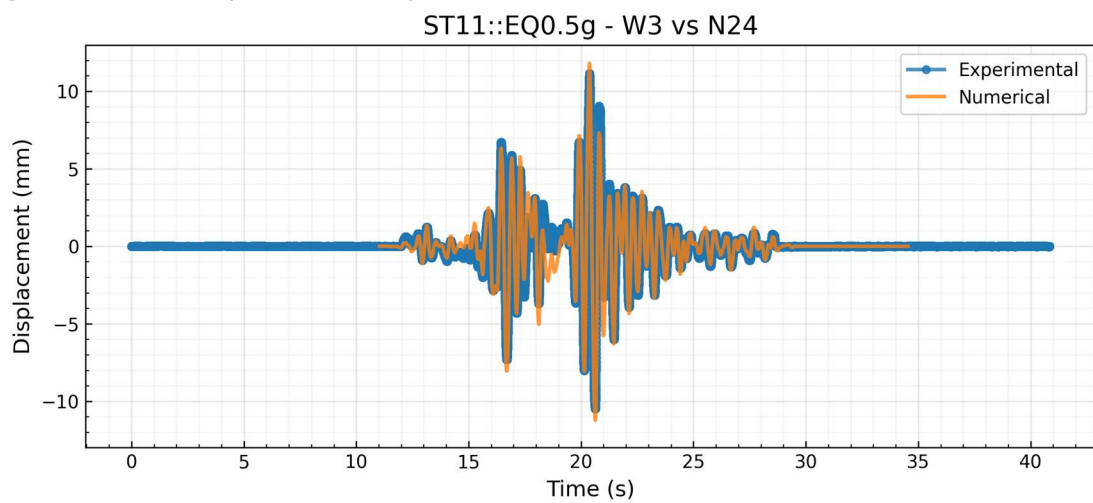


Figure 236 ST11 - Displacement comparison W3 vs N24

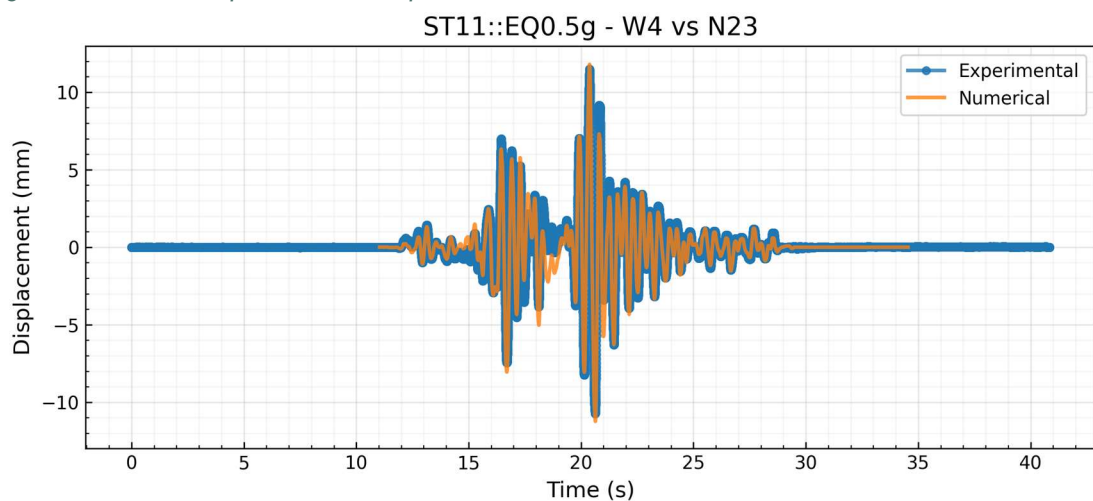


Figure 237 ST11 - Displacement comparison W4 vs N23

6.7 ST13::EQ0.55G RESULTS

The result for draw-wires and accelerometers for ST13::EQ0.55g are presented here.

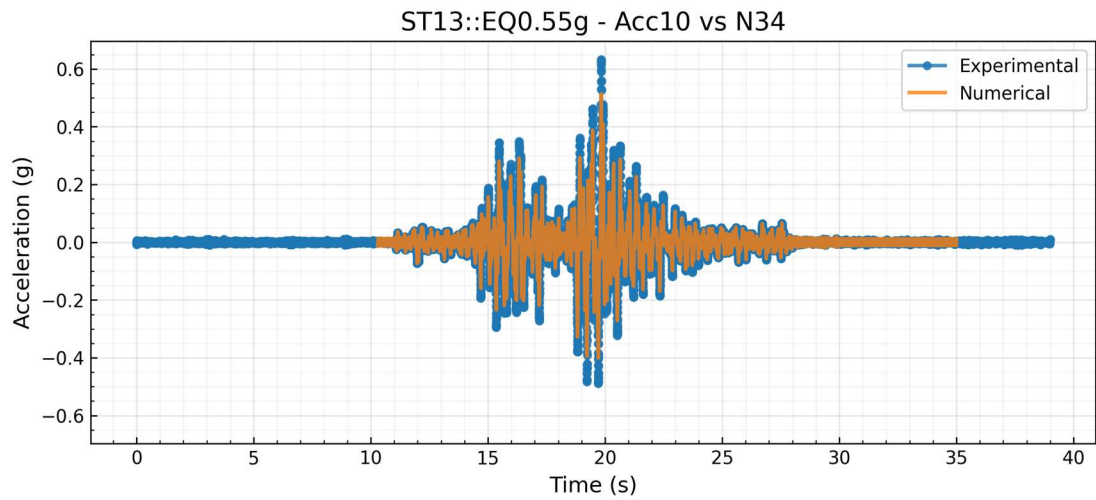


Figure 238 ST13 - Acceleration comparison Acc10 vs N34

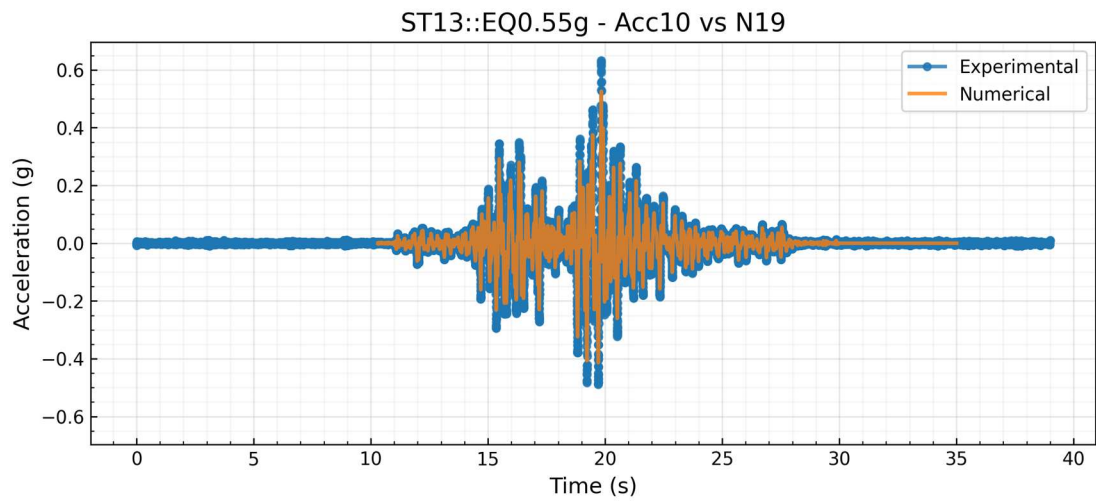


Figure 239 ST13 - Acceleration comparison Acc10 vs N19

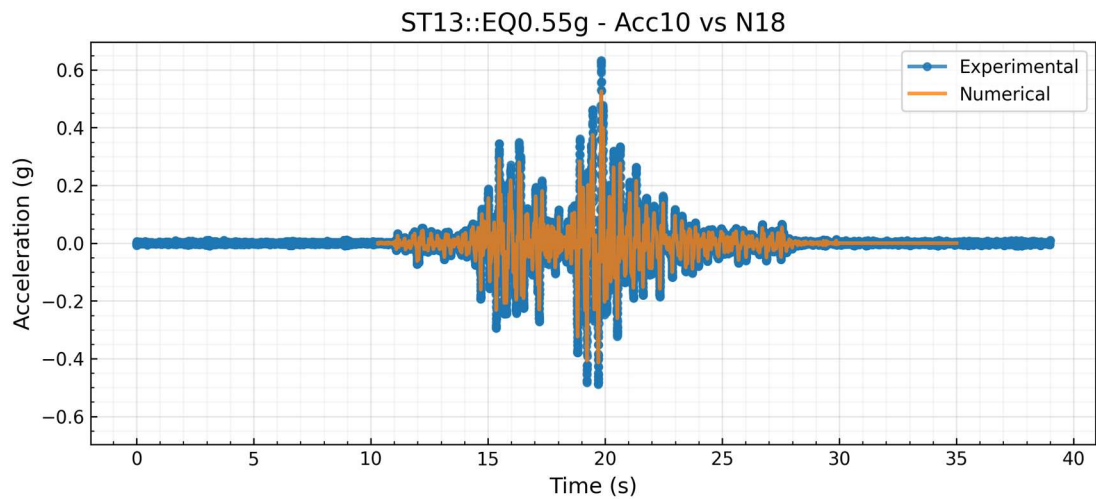


Figure 240 ST13 - Acceleration comparison Acc10 vs N18

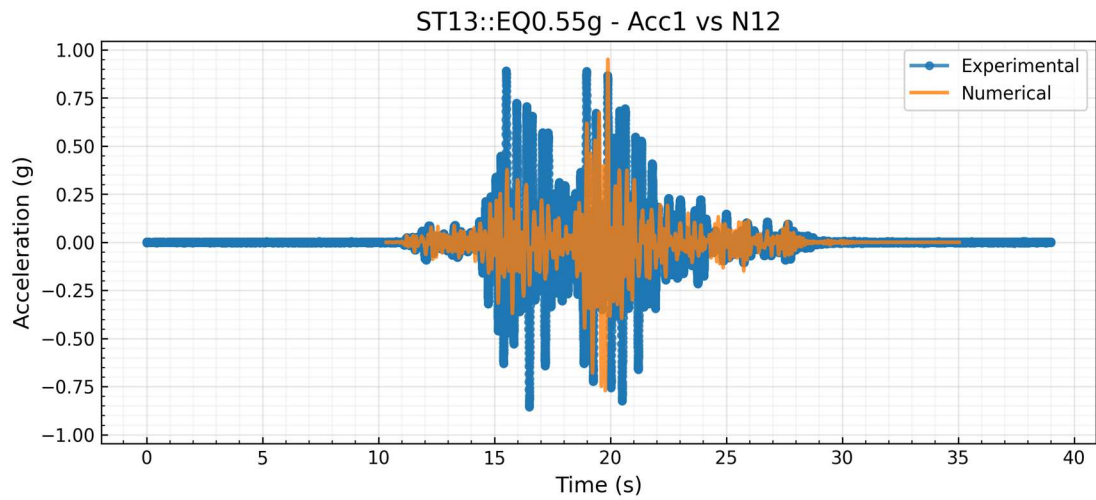


Figure 241 ST13 - Acceleration comparison Acc1 vs N12

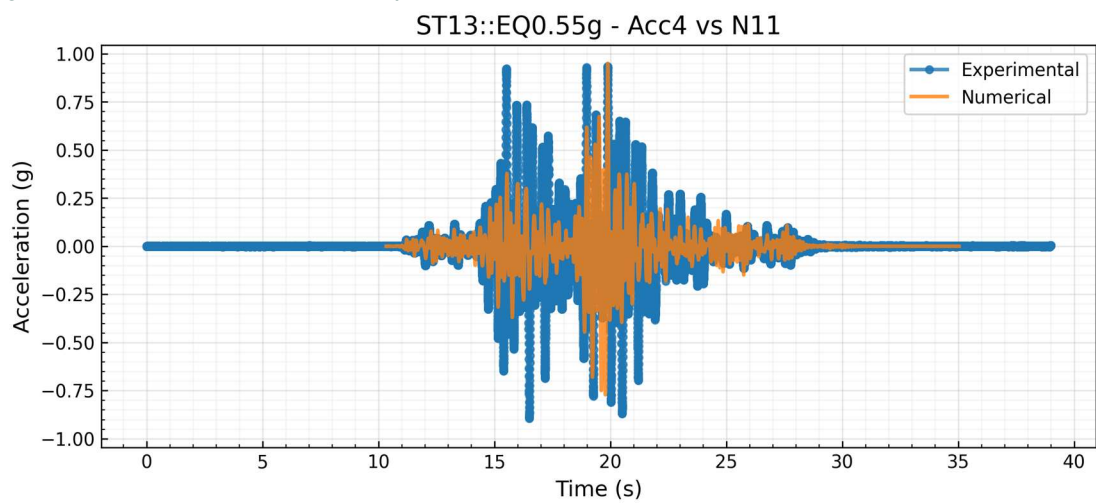


Figure 242 ST13 - Acceleration comparison Acc4 vs N11

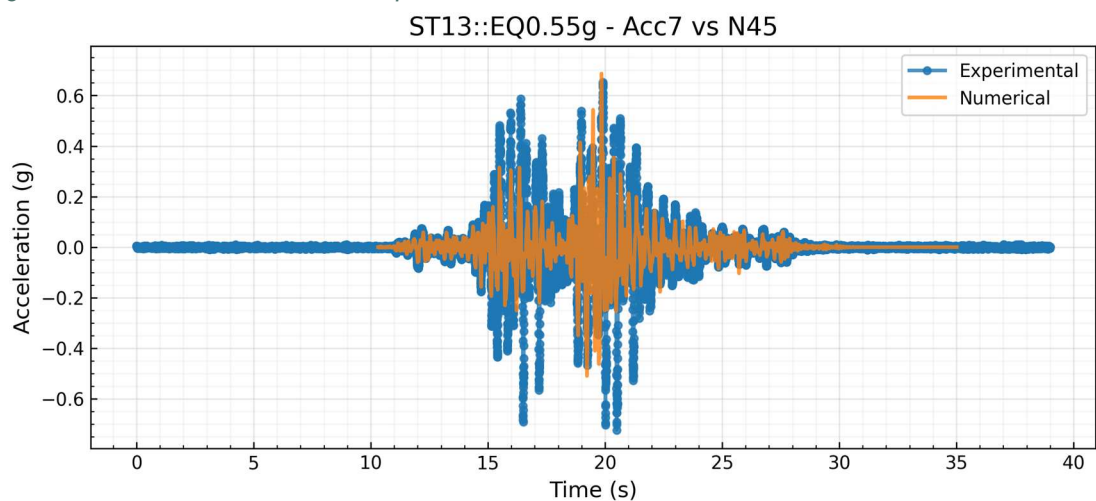


Figure 243 ST13 - Acceleration comparison Acc7 vs N45

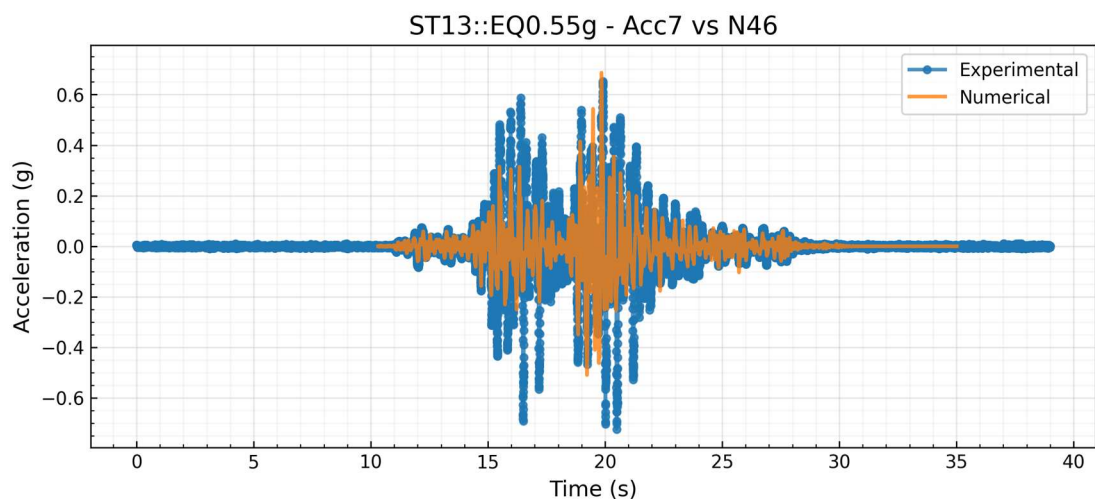


Figure 244 ST13 - Acceleration comparison Acc7 vs N46

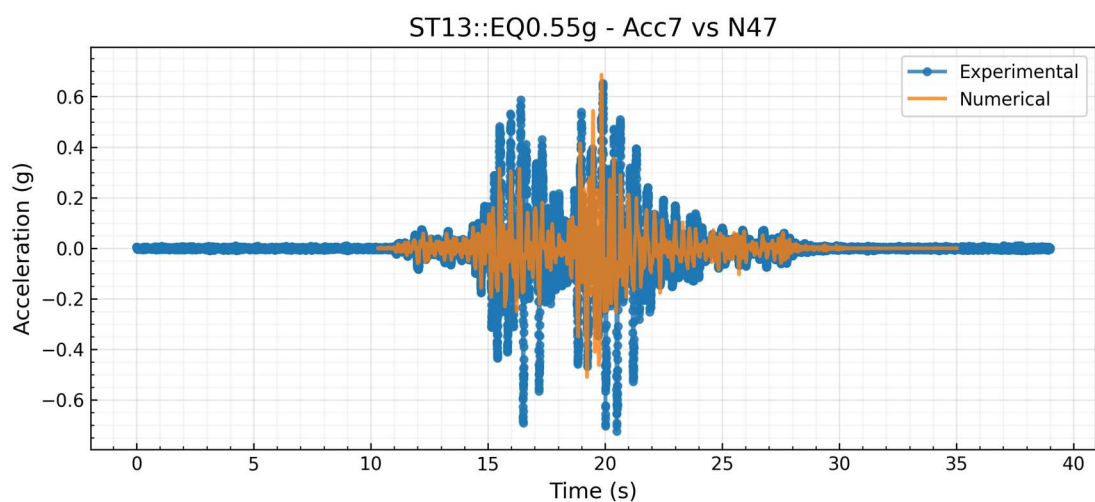


Figure 245 ST13 - Acceleration comparison Acc7 vs N47

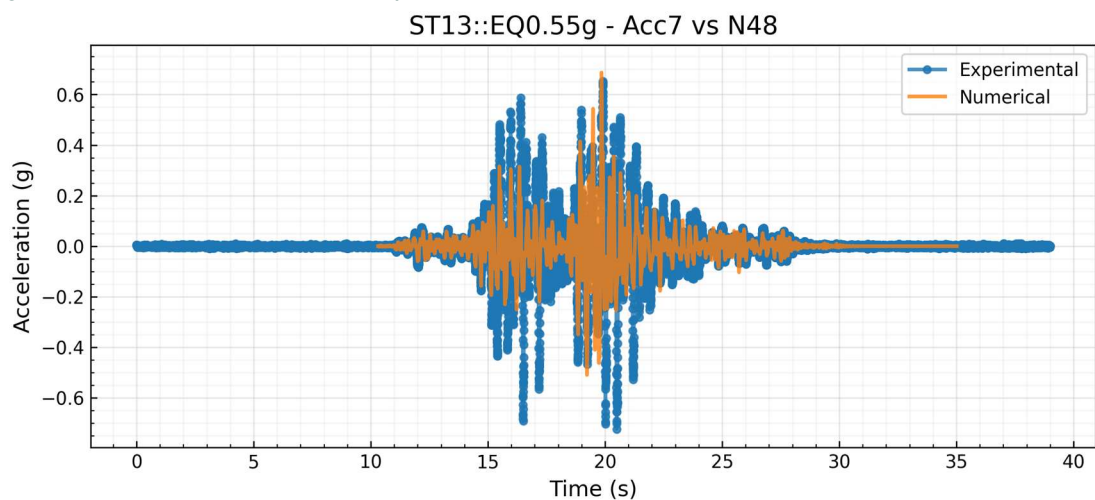


Figure 246 ST13 - Acceleration comparison Acc7 vs N48

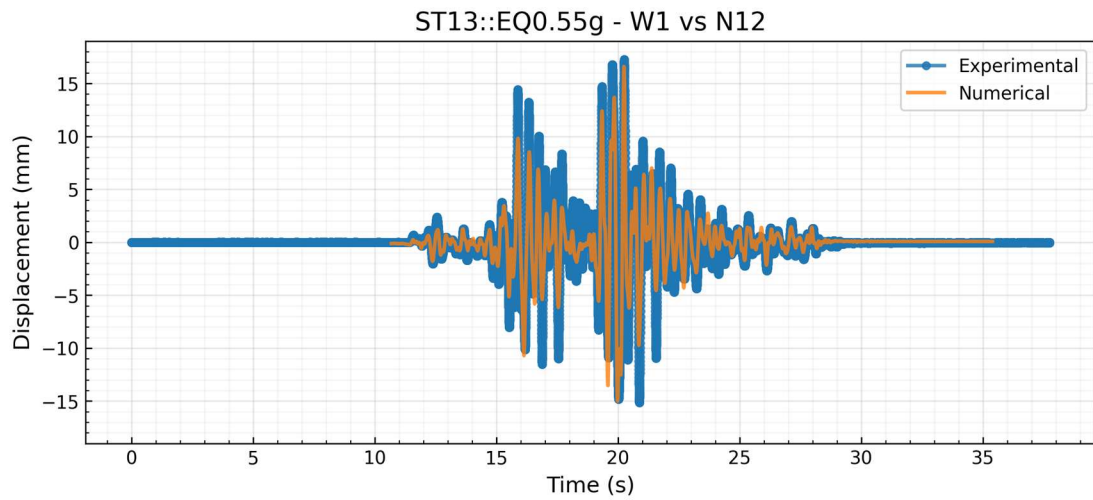


Figure 247 ST13 - Displacement comparison W1 vs N12

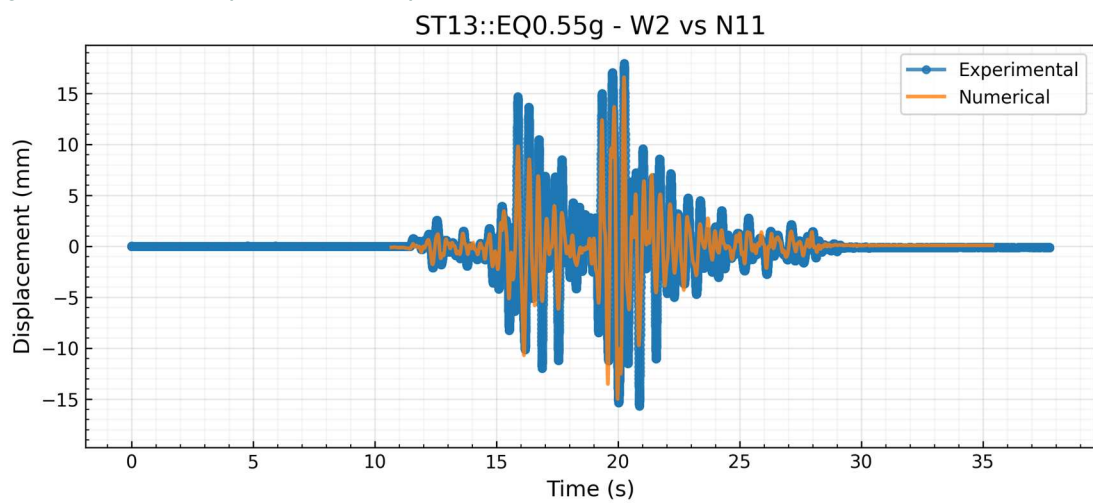


Figure 248 ST13 - Displacement comparison W2 vs N11

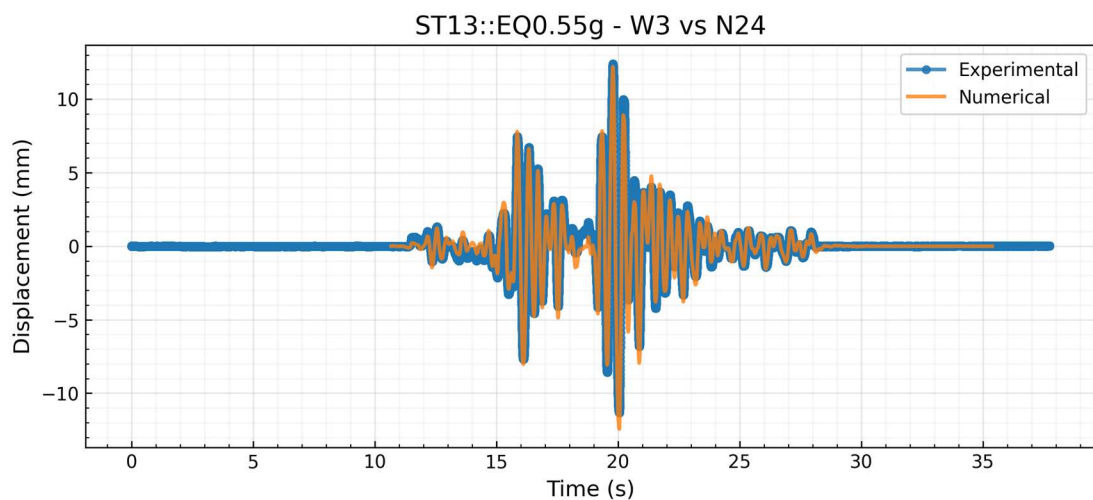


Figure 249 ST13 - Displacement comparison W3 vs N24

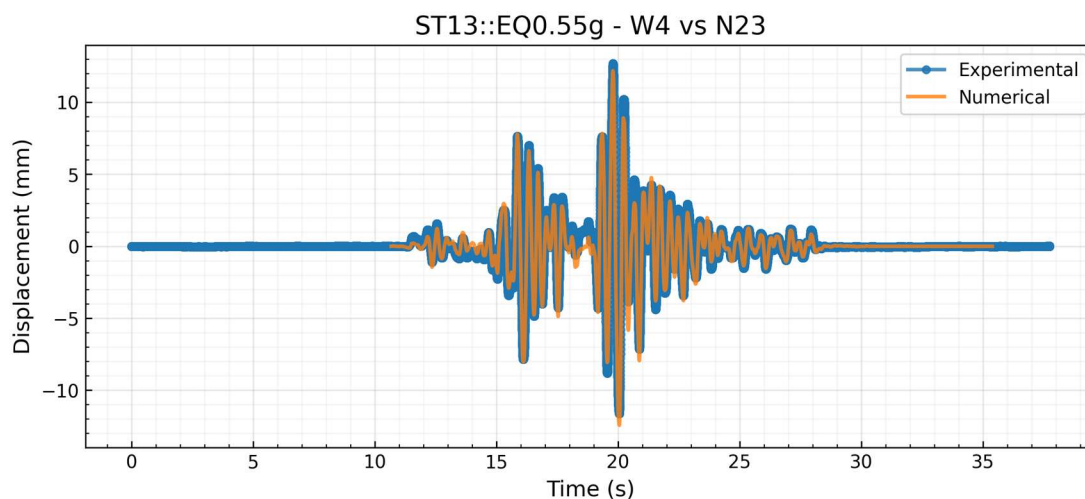


Figure 250 ST13 - Displacement comparison W4 vs N23

6.8 ST15::EQ0.74G RESULTS

The result for draw-wires and accelerometers for ST15::EQ0.74g are presented here.

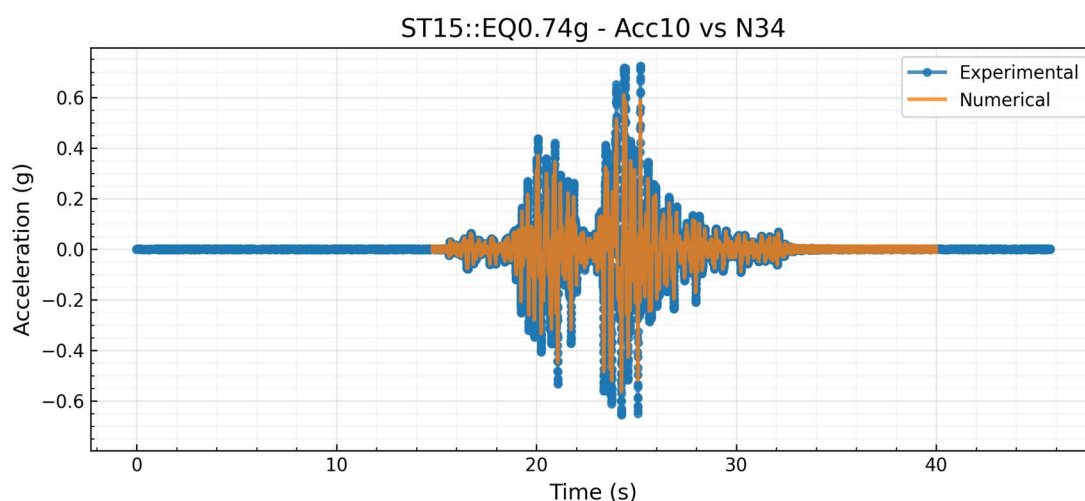


Figure 251 ST15 - Acceleration comparison Acc10 vs N34

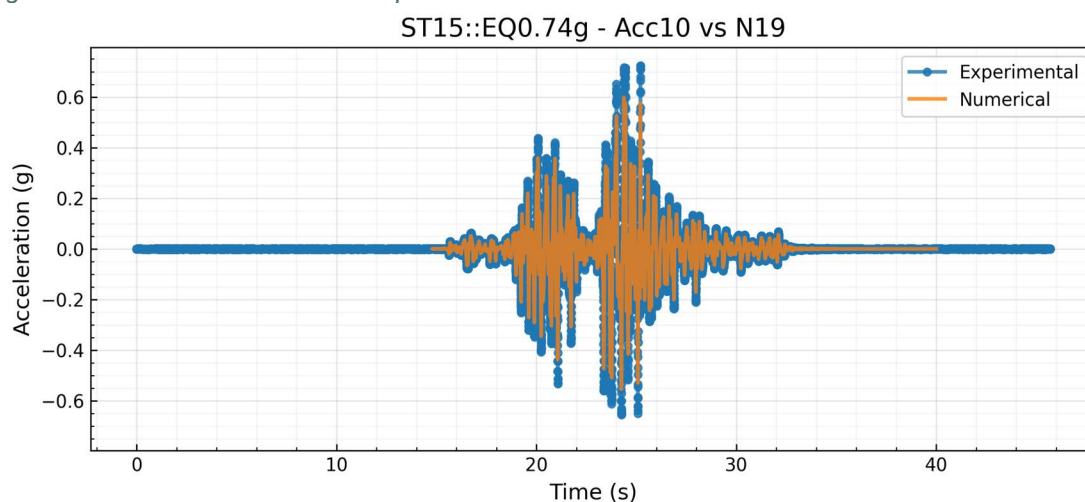


Figure 252 ST15 - Acceleration comparison Acc10 vs N19

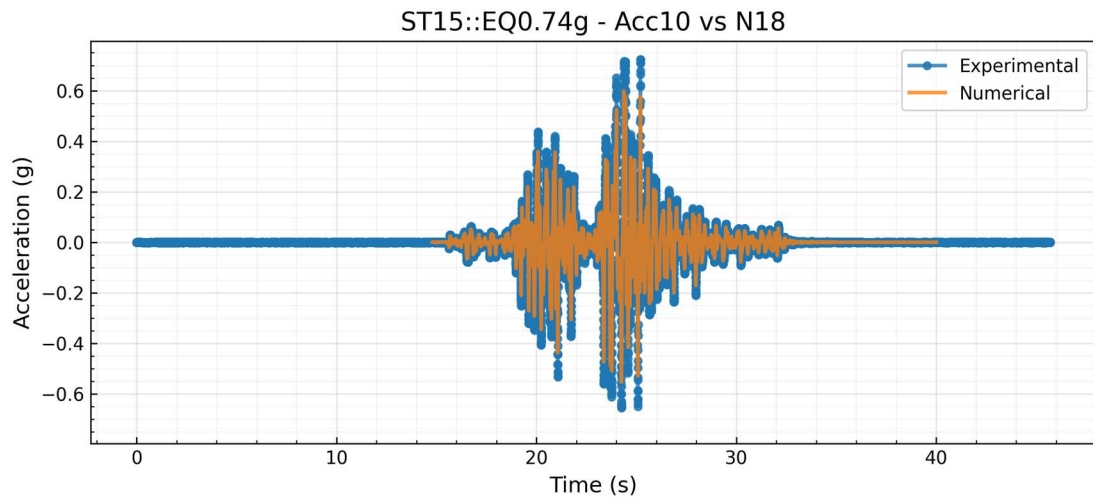


Figure 253 ST15 - Acceleration comparison Acc10 vs N18

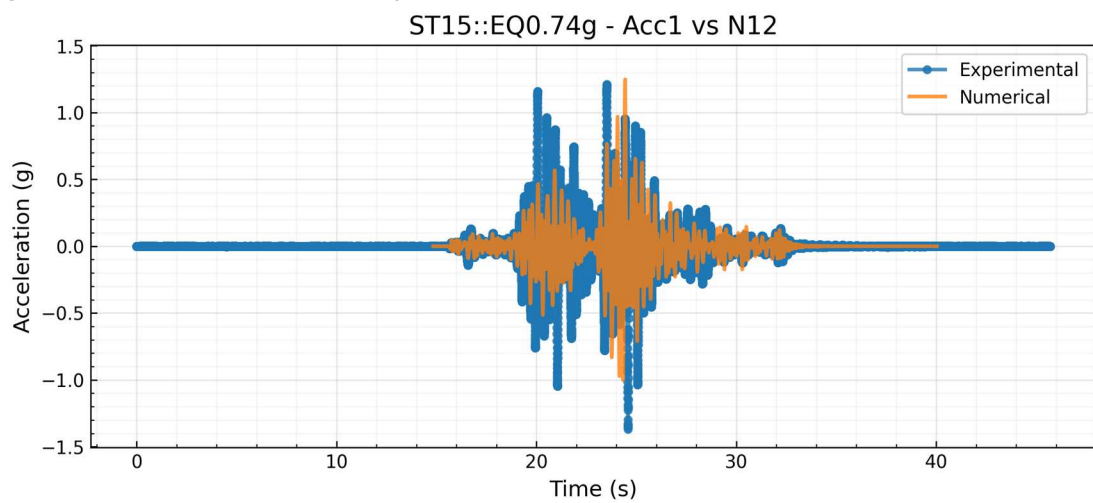


Figure 254 ST15 - Acceleration comparison Acc1 vs N12

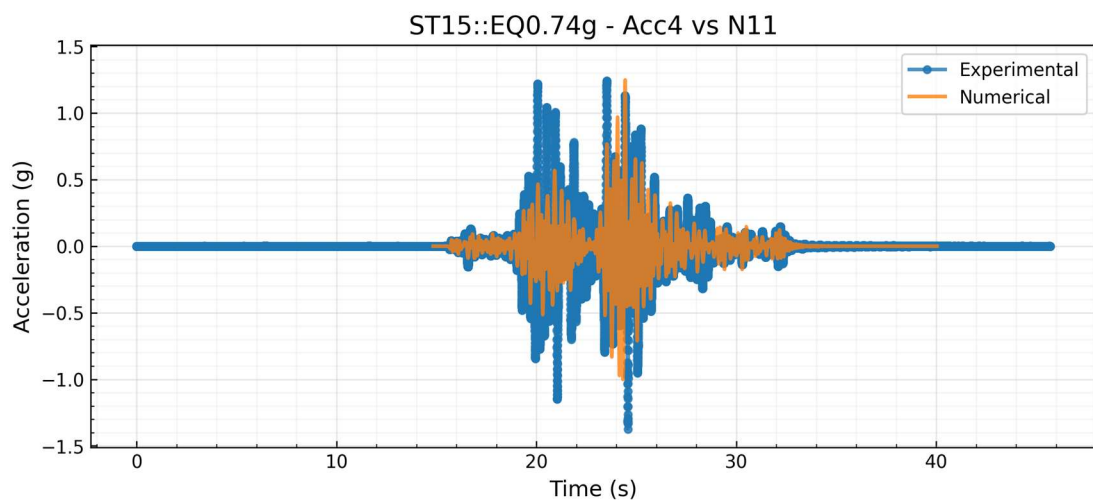


Figure 255 ST15 - Acceleration comparison Acc4 vs N11

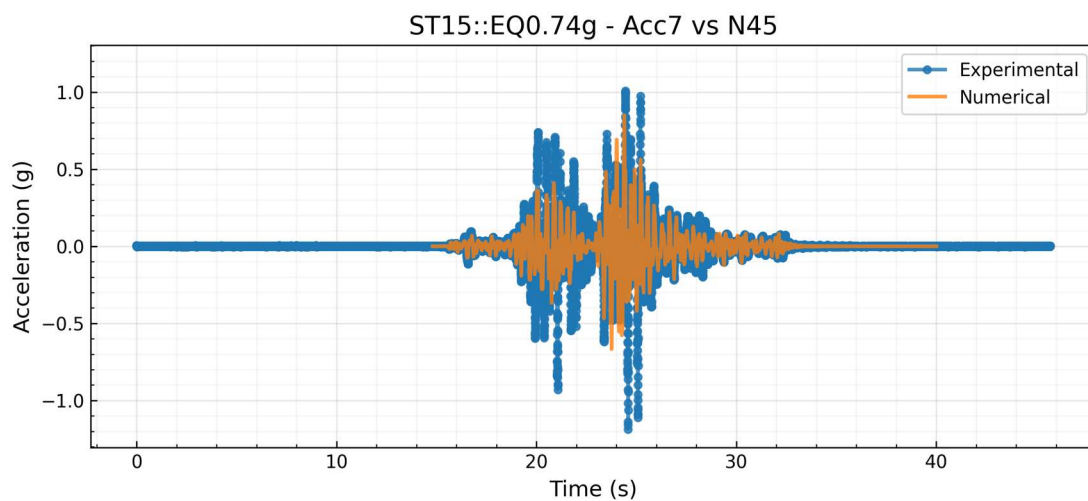


Figure 256 ST15 - Acceleration comparison Acc7 vs N45

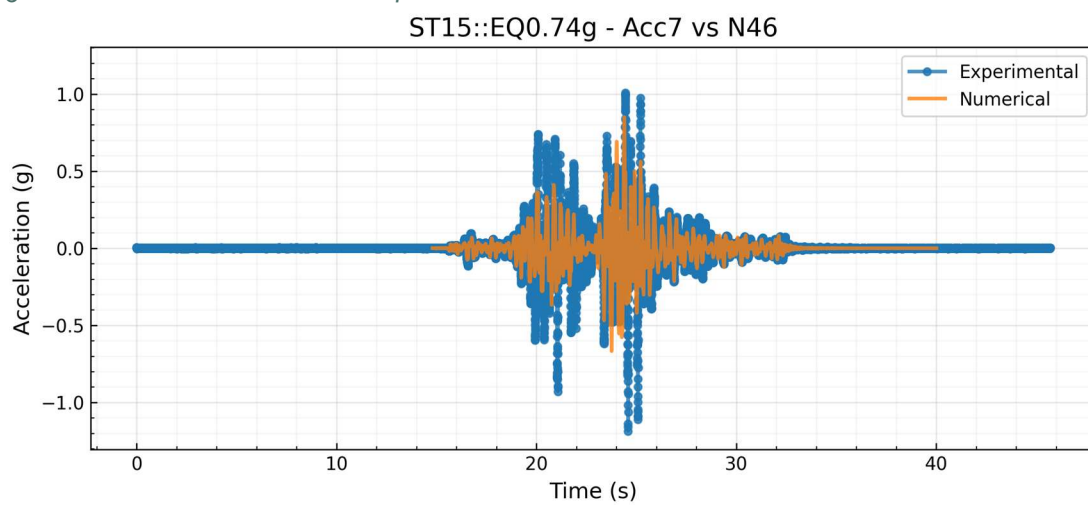


Figure 257 ST15 - Acceleration comparison Acc7 vs N46

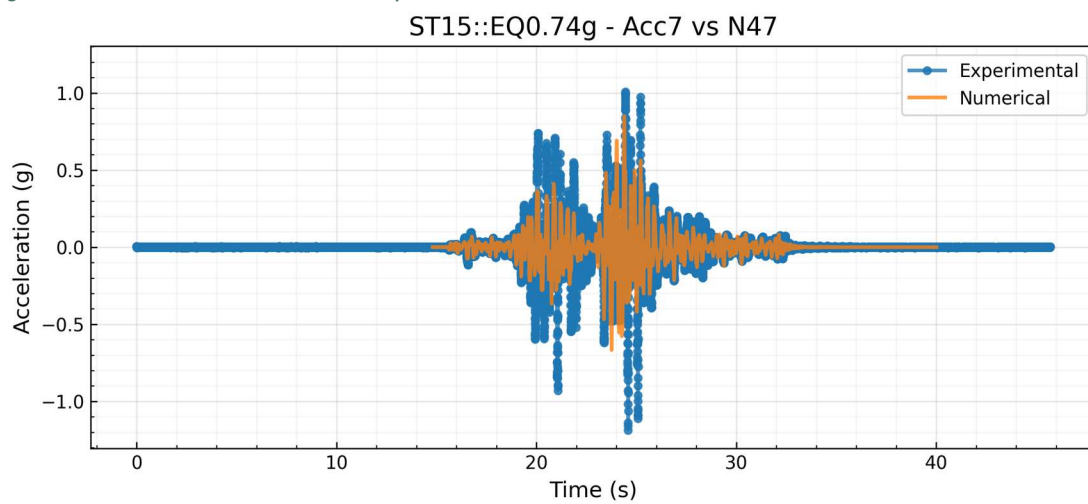


Figure 258 ST15 - Acceleration comparison Acc7 vs N47

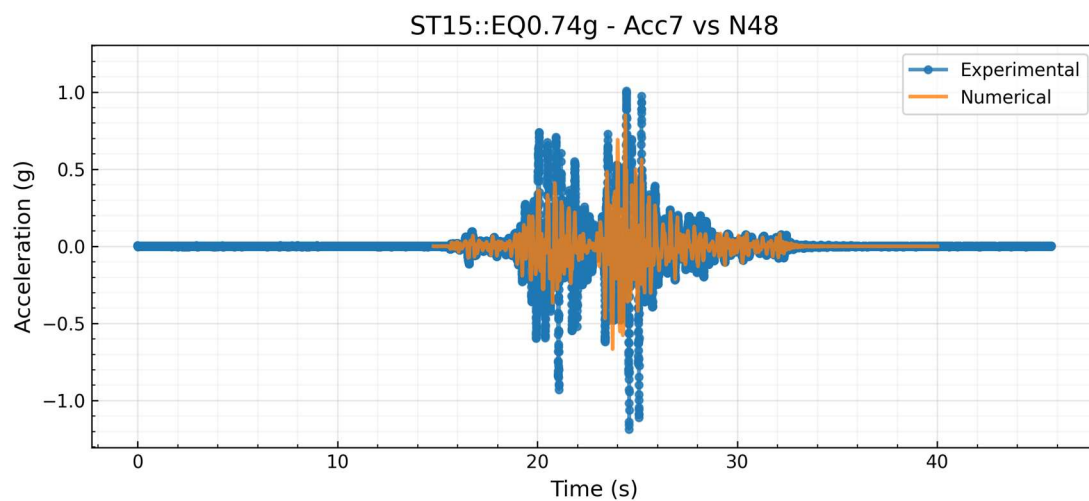


Figure 259 ST15 - Acceleration comparison Acc7 vs N48

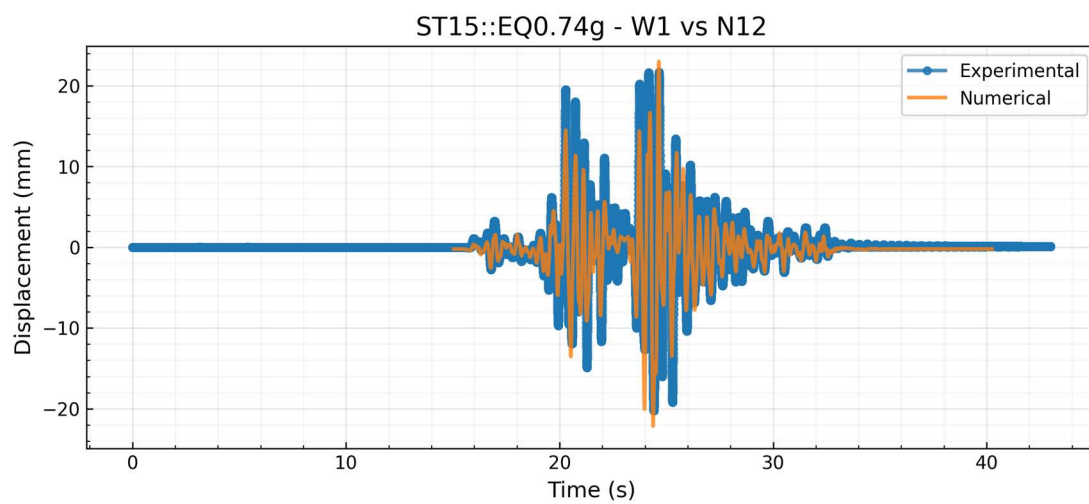


Figure 260 ST15 - Displacement comparison W1 vs N12

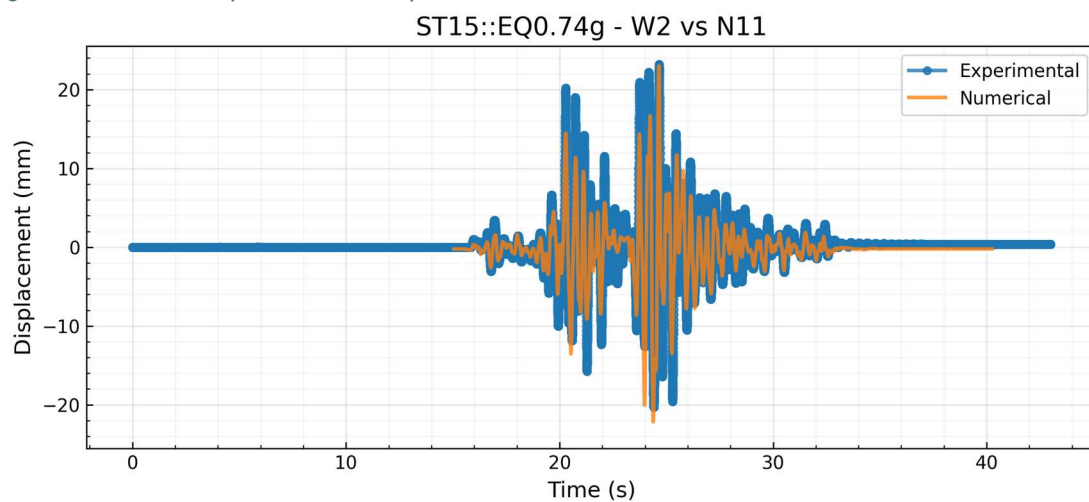


Figure 261 ST15 - Displacement comparison W2 vs N11

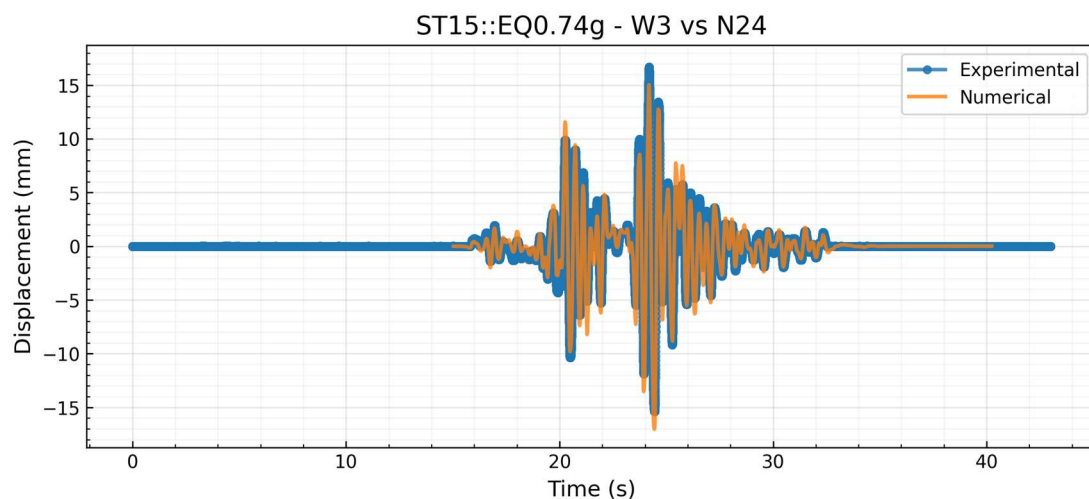


Figure 262 ST15 - Displacement comparison W3 vs N24

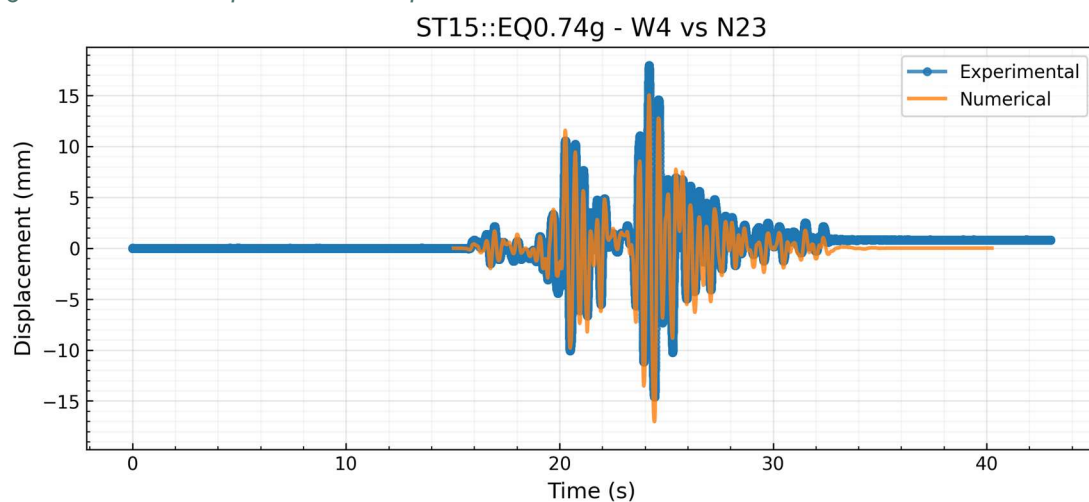


Figure 263 ST15 - Displacement comparison W4 vs N23

6.9 ST17::EQ0.8G RESULTS

The result for draw-wires and accelerometers for ST17::EQ0.8g are presented here.

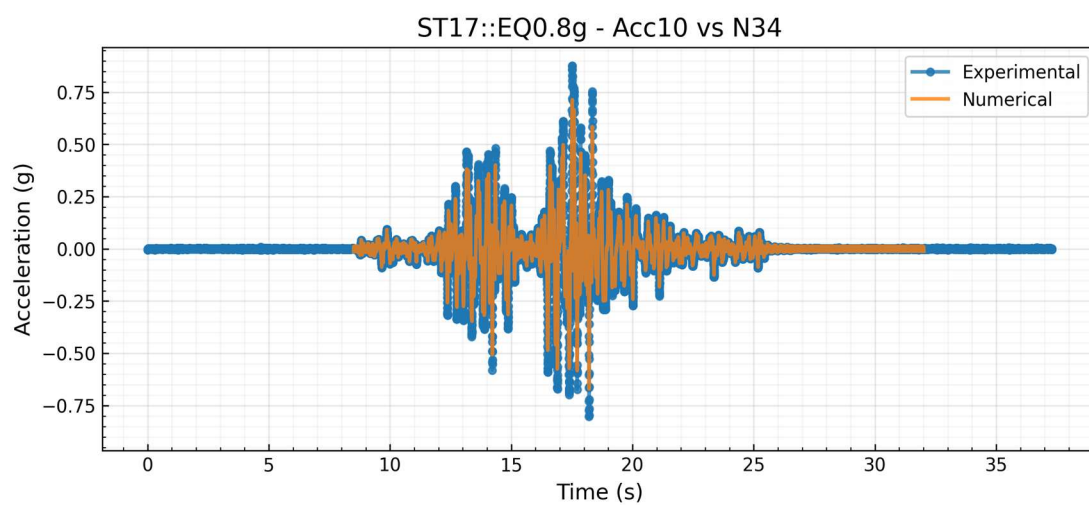


Figure 264 ST17 - Acceleration comparison Acc10 vs N34

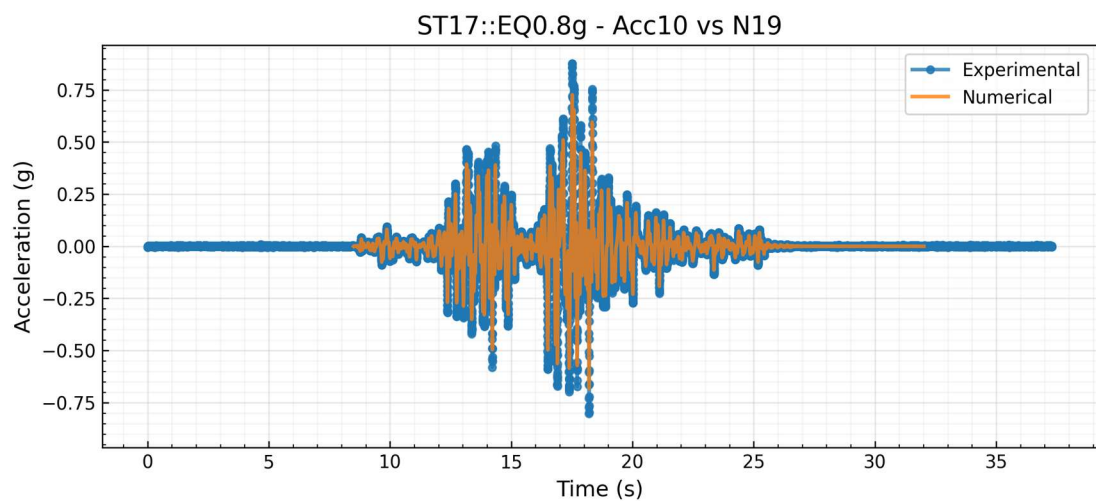


Figure 265 ST17 - Acceleration comparison Acc10 vs N19

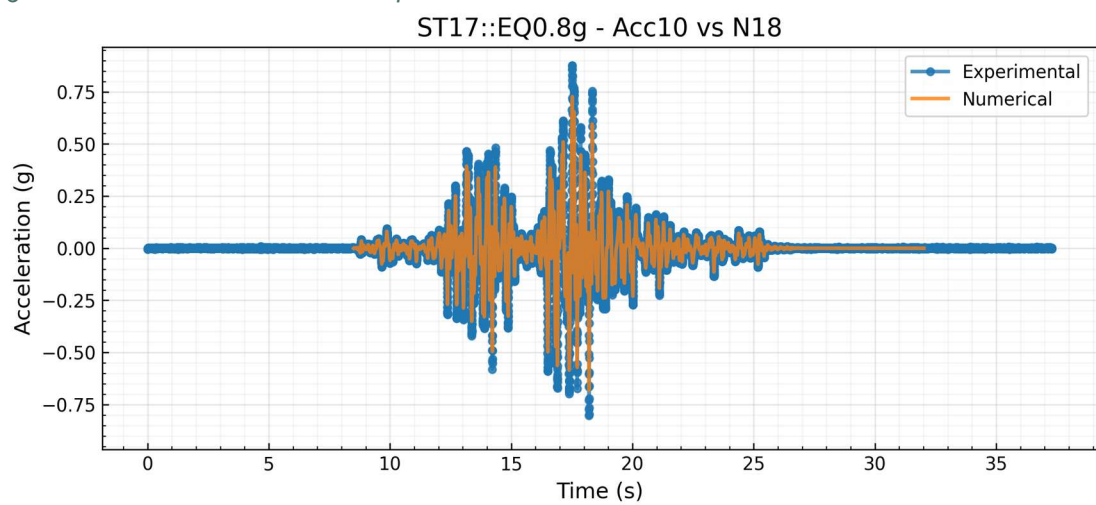


Figure 266 ST17 - Acceleration comparison Acc10 vs N18

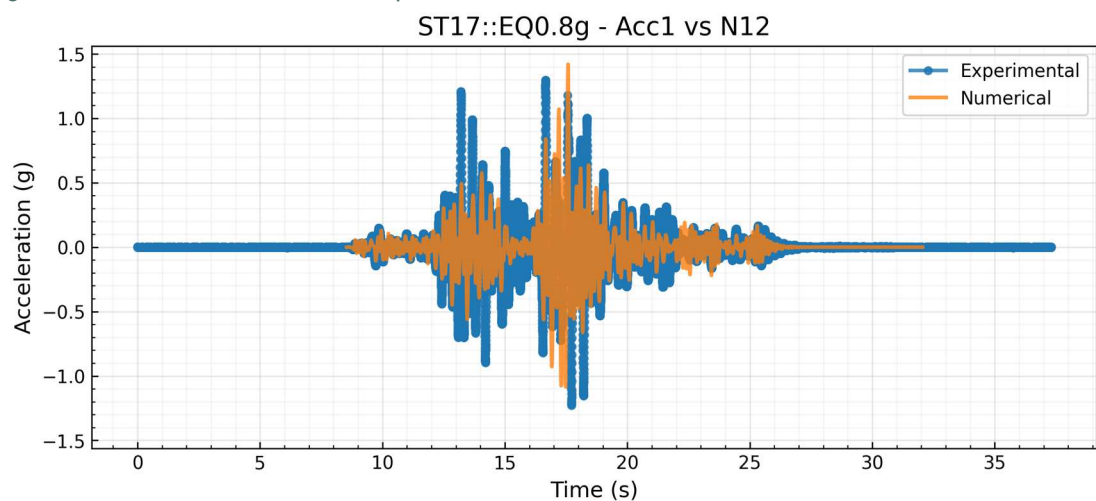


Figure 267 ST17 - Acceleration comparison Acc1 vs N12

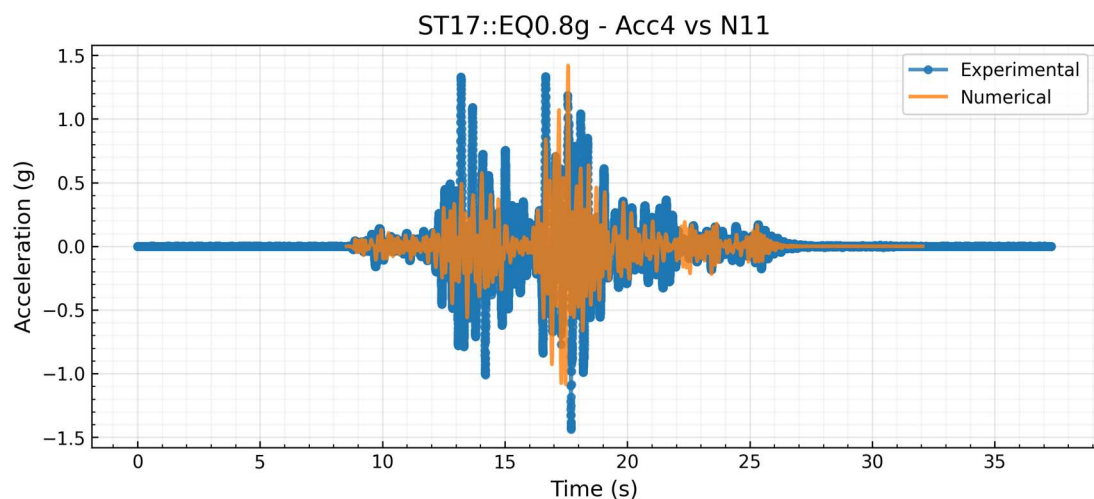


Figure 268 ST17 - Acceleration comparison Acc4 vs N11

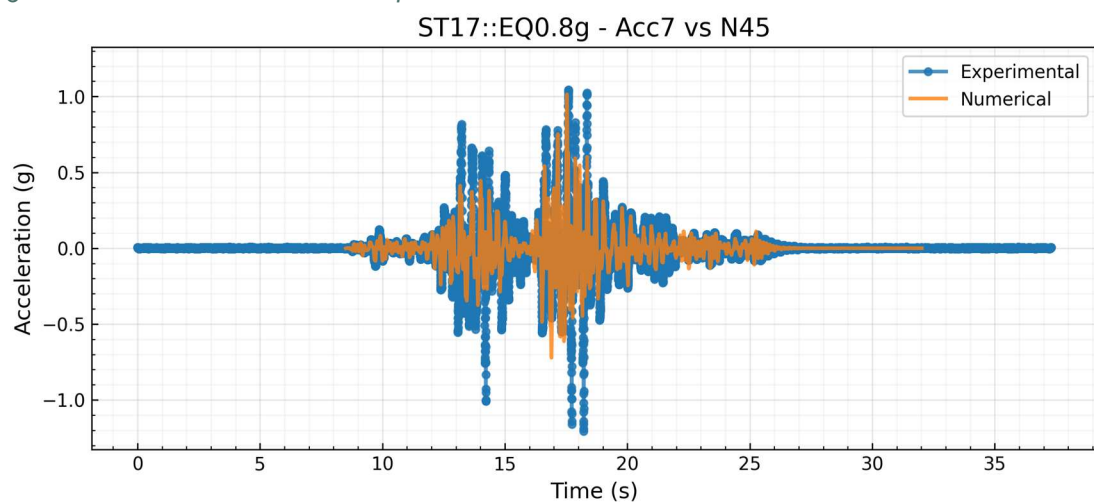


Figure 269 ST17 - Acceleration comparison Acc7 vs N45

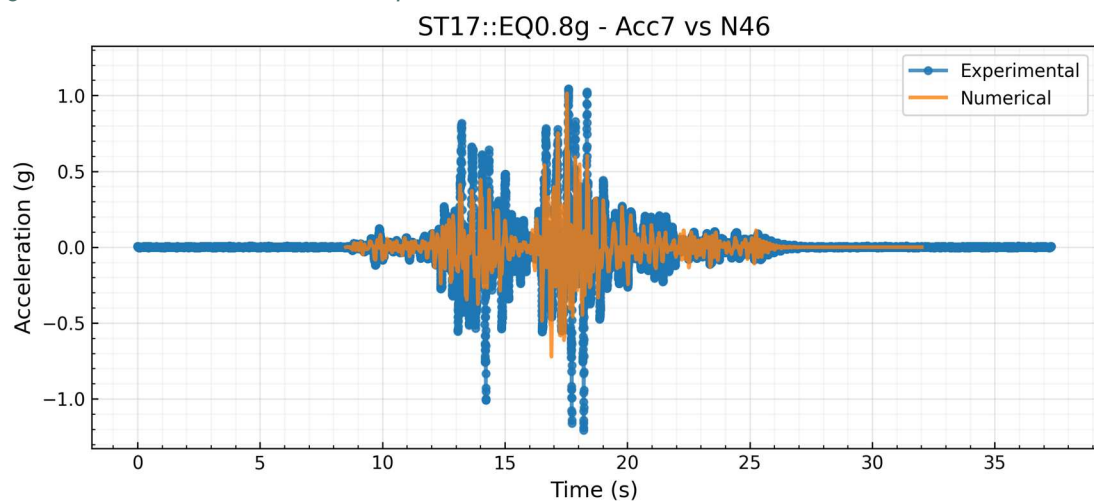


Figure 270 ST17 - Acceleration comparison Acc7 vs N46

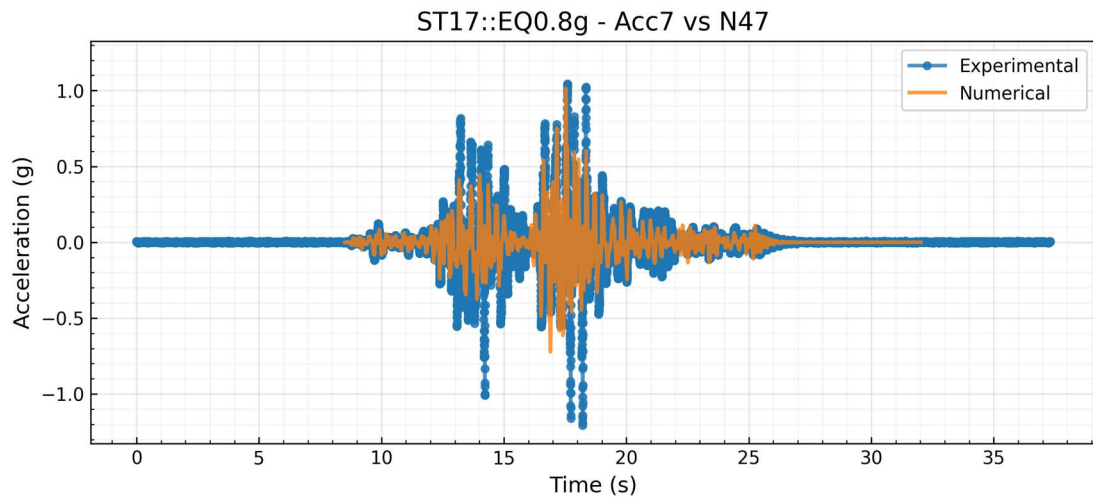


Figure 271 ST17 - Acceleration comparison Acc7 vs N47

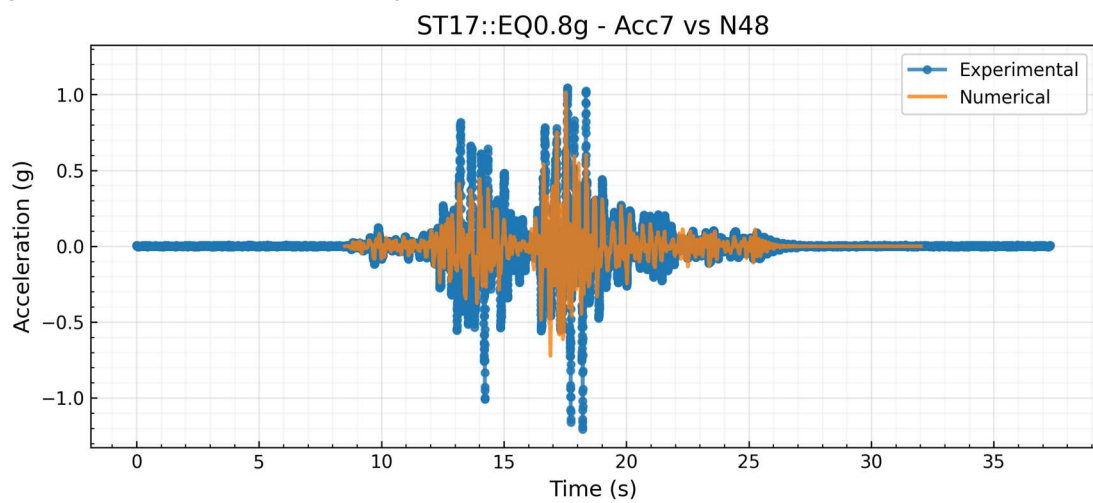


Figure 272 ST17 - Acceleration comparison Acc7 vs N48

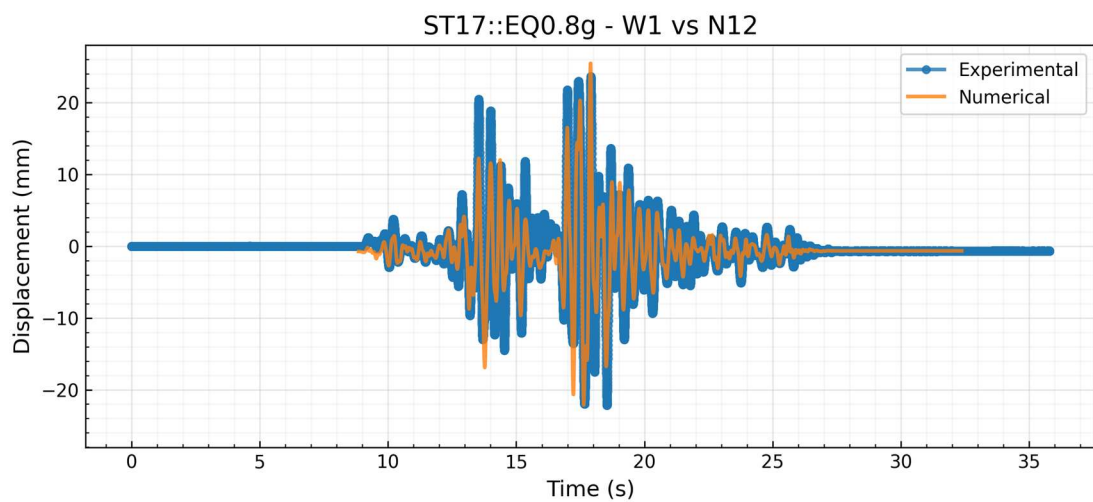


Figure 273 ST17 - Displacement comparison W1 vs N12

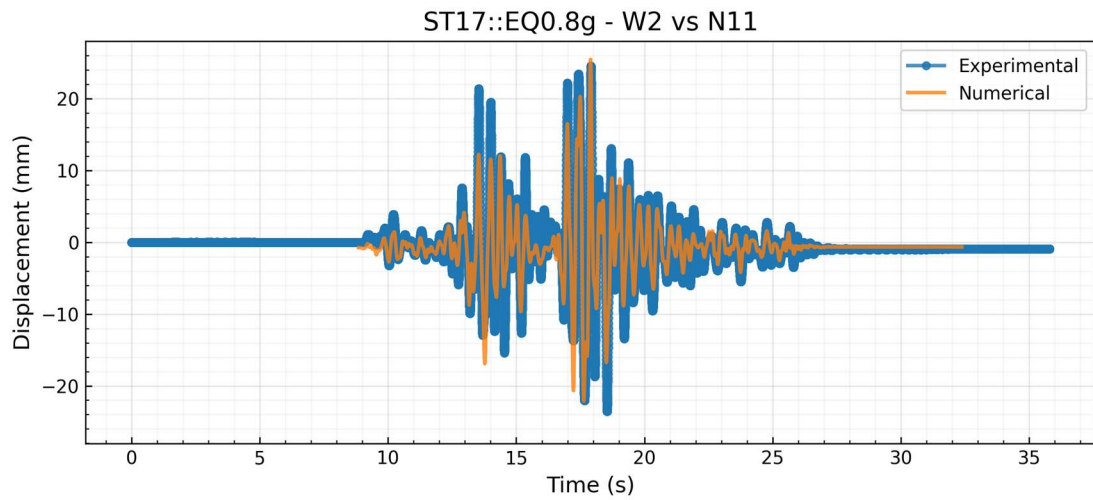


Figure 274 ST17 - Displacement comparison W2 vs N11

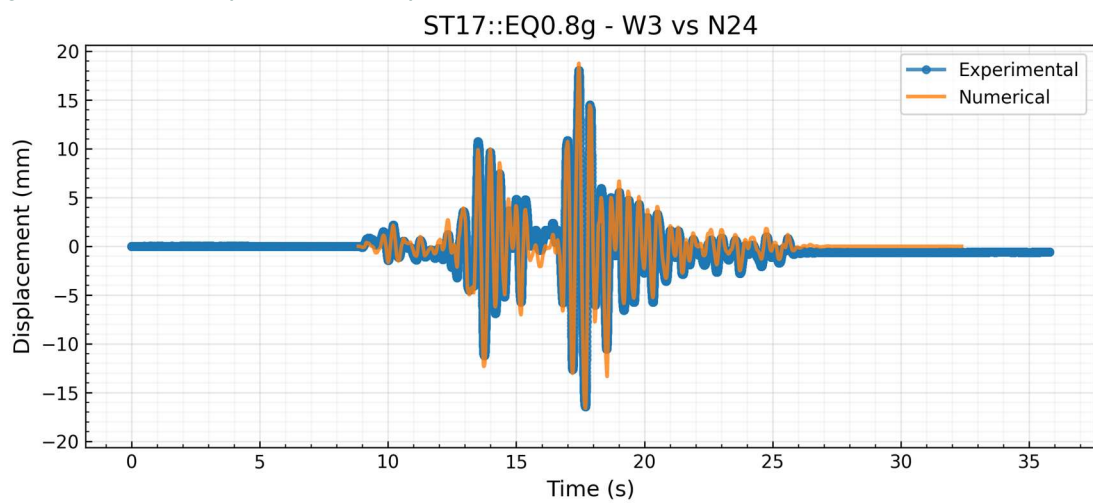


Figure 275 ST17 - Displacement comparison W3 vs N24

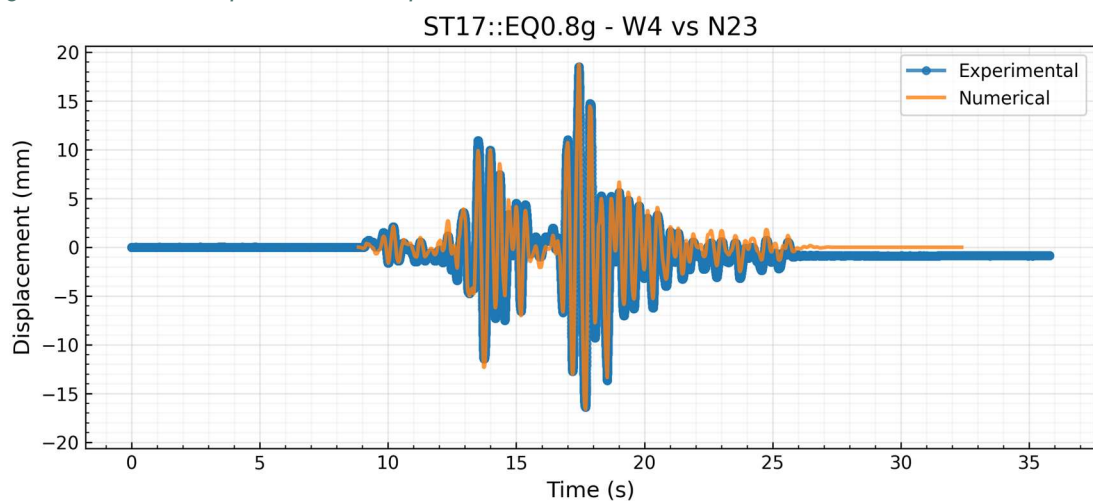


Figure 276 ST17 - Displacement comparison W4 vs N23

6.10 ST19::EQ1.1G RESULTS

The result for draw-wires and accelerometers for ST19::EQ1.1g are presented here.

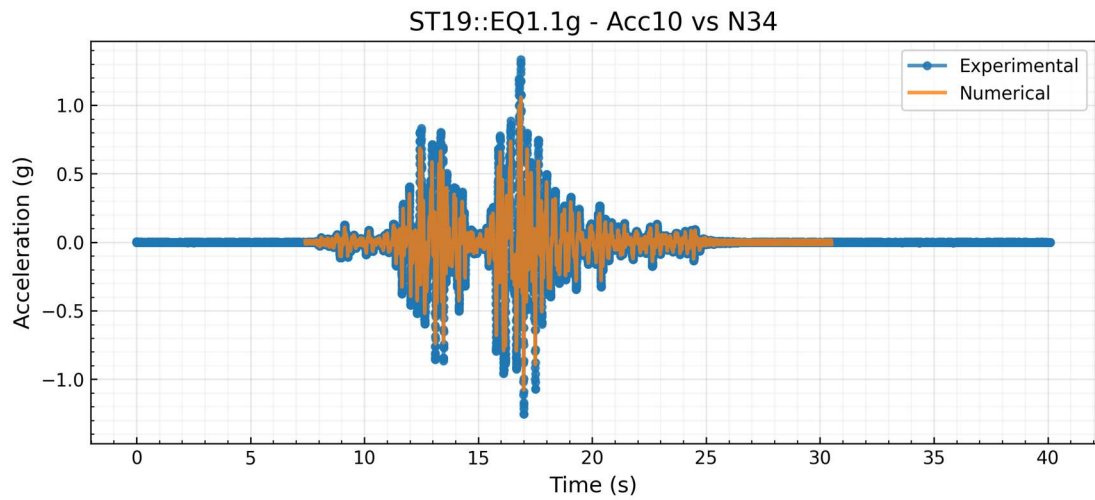


Figure 277 ST19 - Acceleration comparison Acc10 vs N34

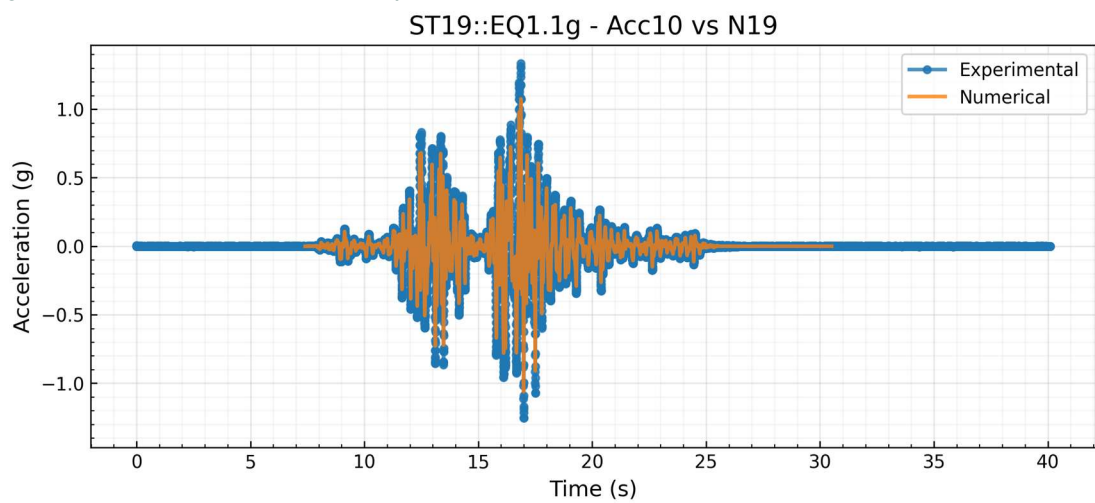


Figure 278 ST19 - Acceleration comparison Acc10 vs N19

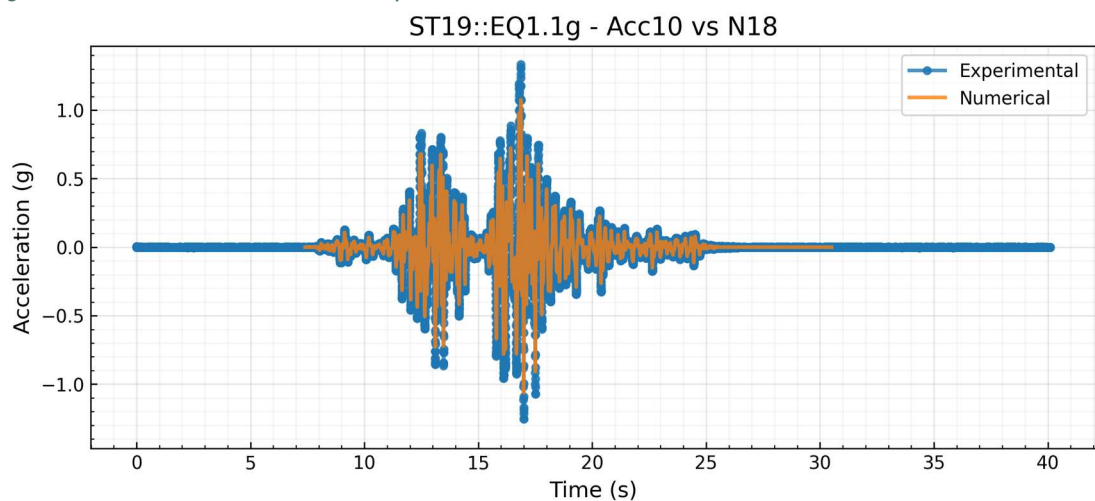


Figure 279 ST19 - Acceleration comparison Acc10 vs N18

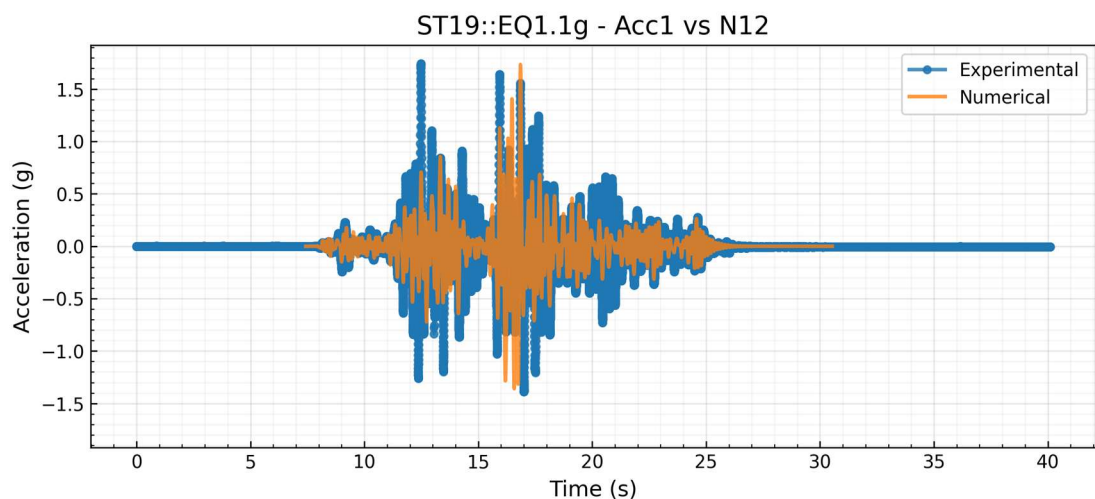


Figure 280 ST19 - Acceleration comparison Acc1 vs N12

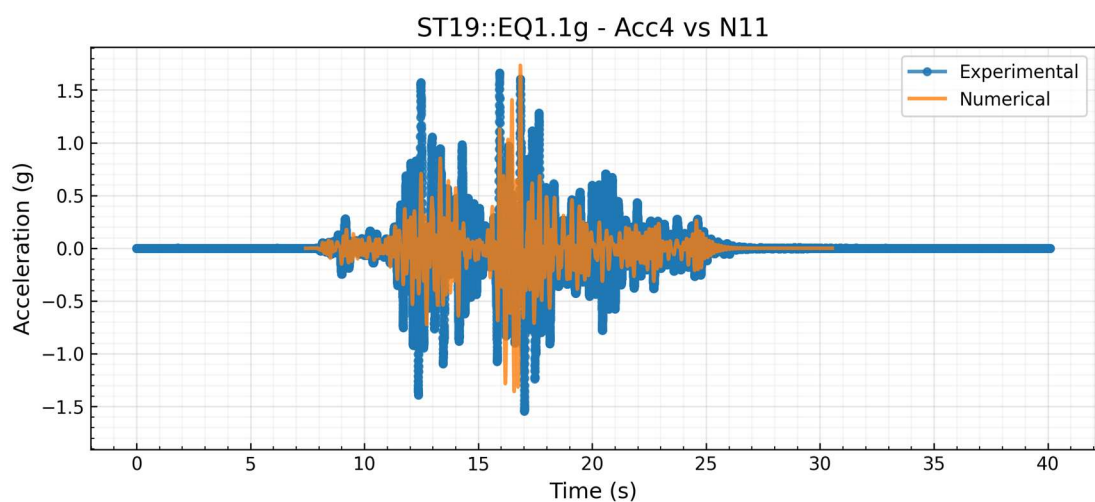


Figure 281 ST19 - Acceleration comparison Acc4 vs N11

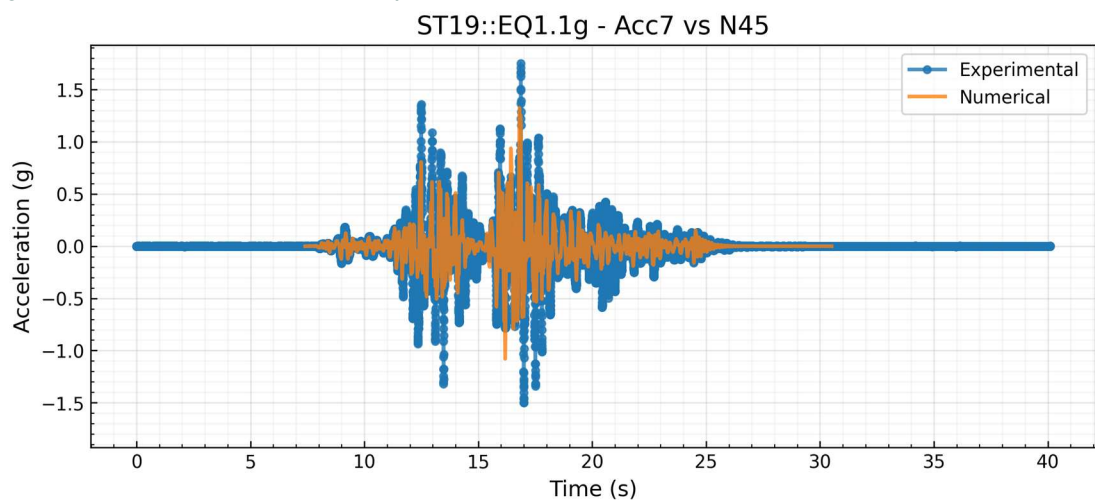


Figure 282 ST19 - Acceleration comparison Acc7 vs N45

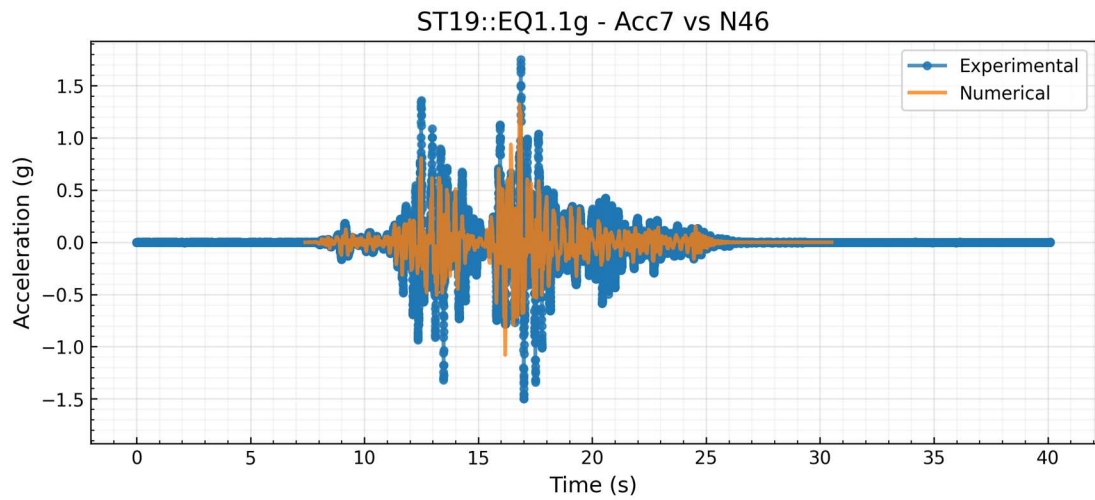


Figure 283 ST19 - Acceleration comparison Acc7 vs N46

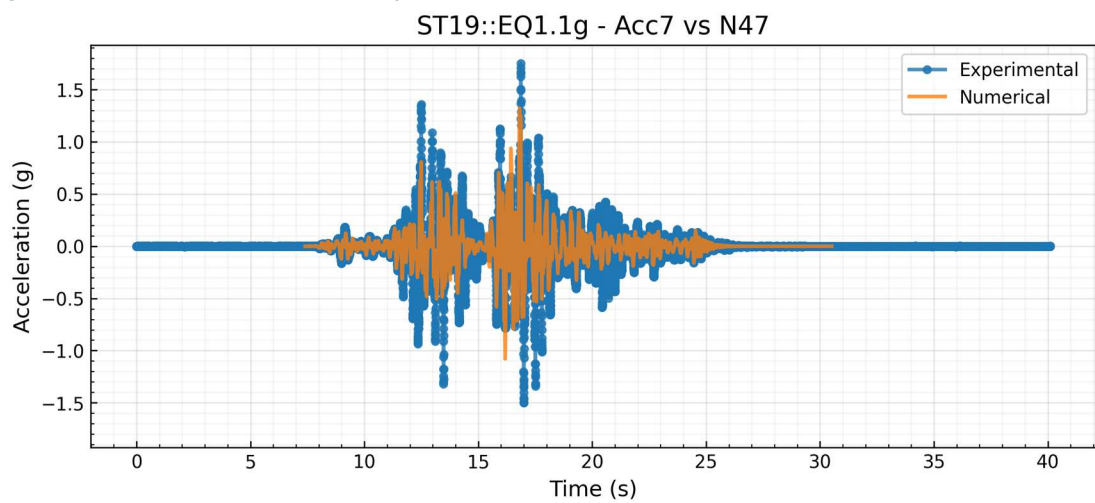


Figure 284 ST19 - Acceleration comparison Acc7 vs N47

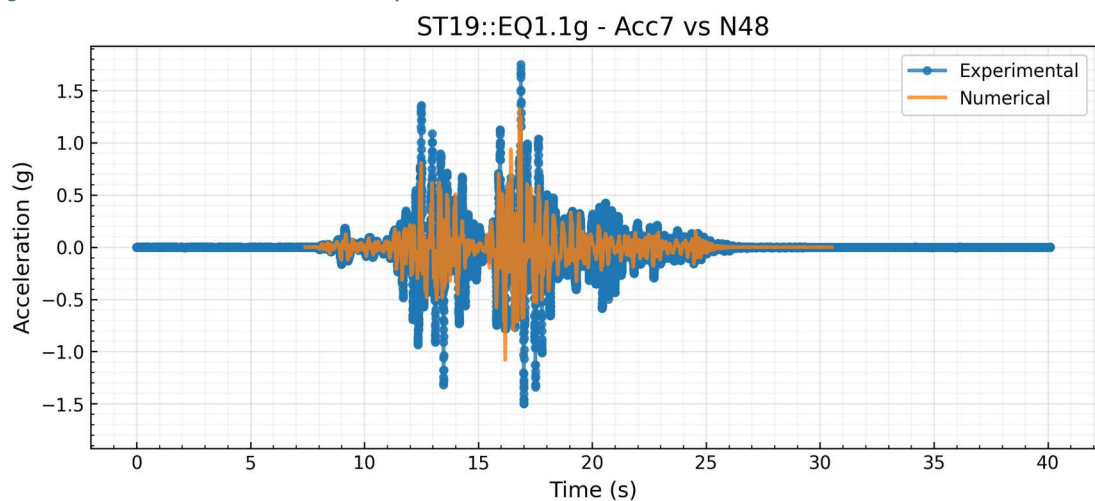


Figure 285 ST19 - Acceleration comparison Acc7 vs N48

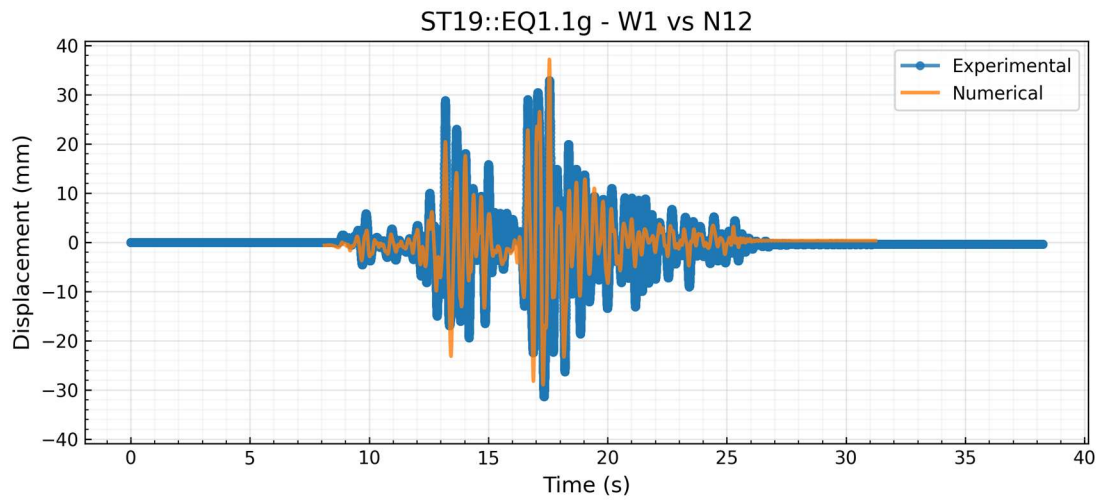


Figure 286 ST19 - Displacement comparison W1 vs N12

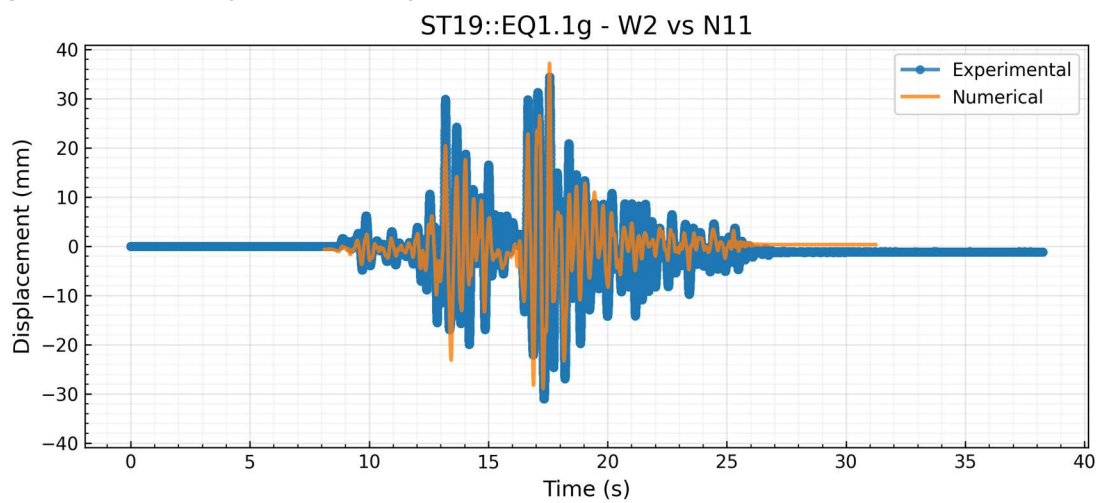


Figure 287 ST19 - Displacement comparison W2 vs N11

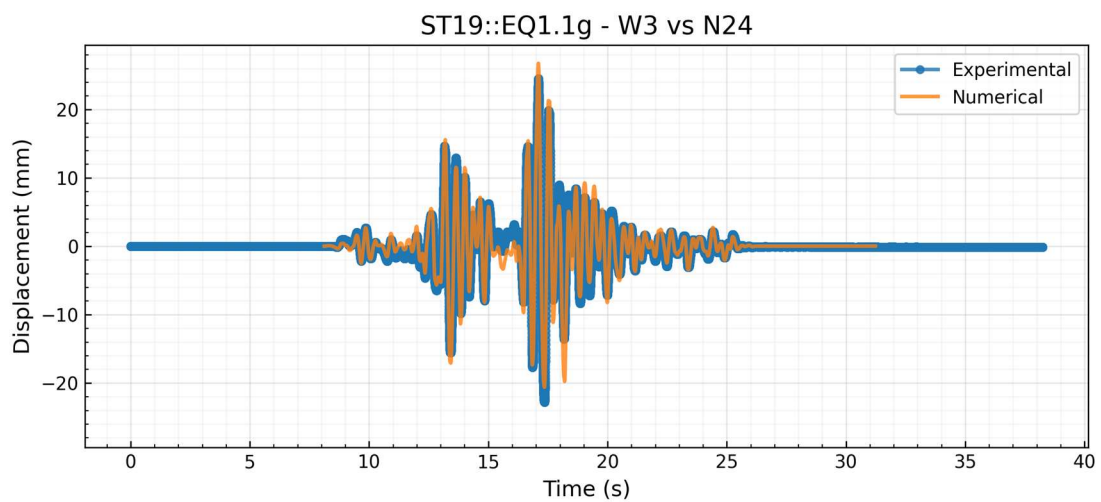


Figure 288 ST19 - Displacement comparison W3 vs N24

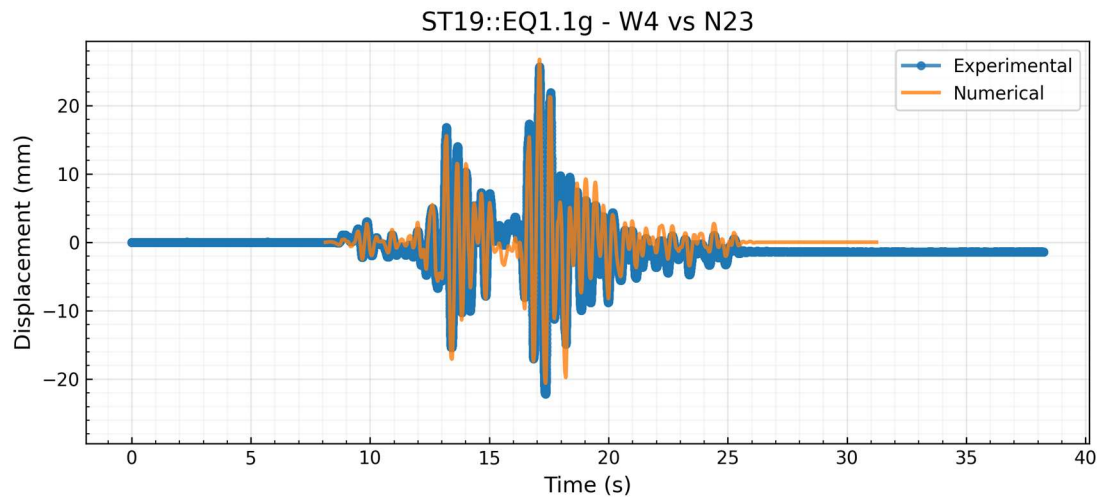


Figure 289 ST19 - Displacement comparison W4 vs N23

6.11 ST21::EQ1.3G RESULTS

The result for draw-wires for ST21::EQ1.3g are presented here.

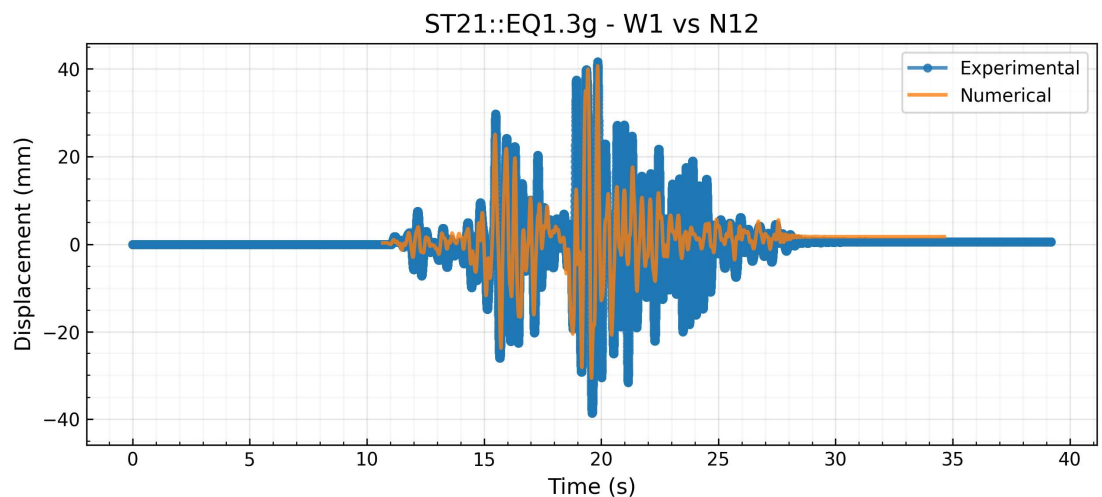


Figure 290 ST21 - Displacement comparison W1 vs N12

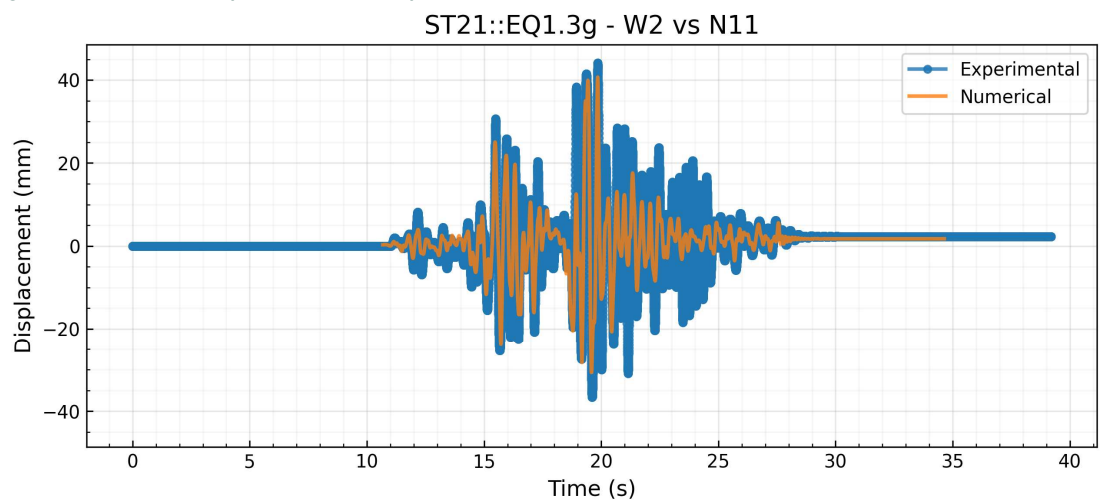


Figure 291 ST21 - Displacement comparison W2 vs N11

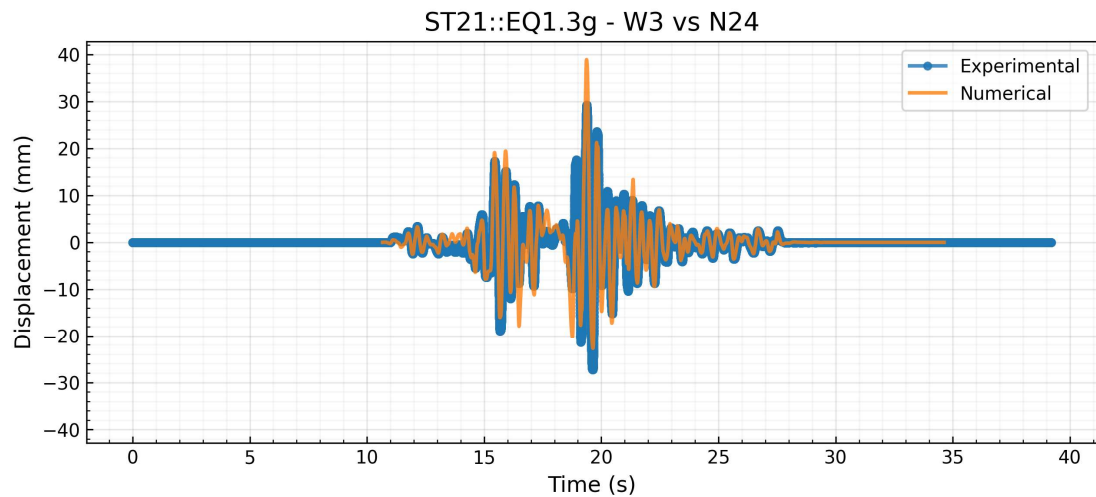


Figure 292 ST21 - Displacement comparison W3 vs N24

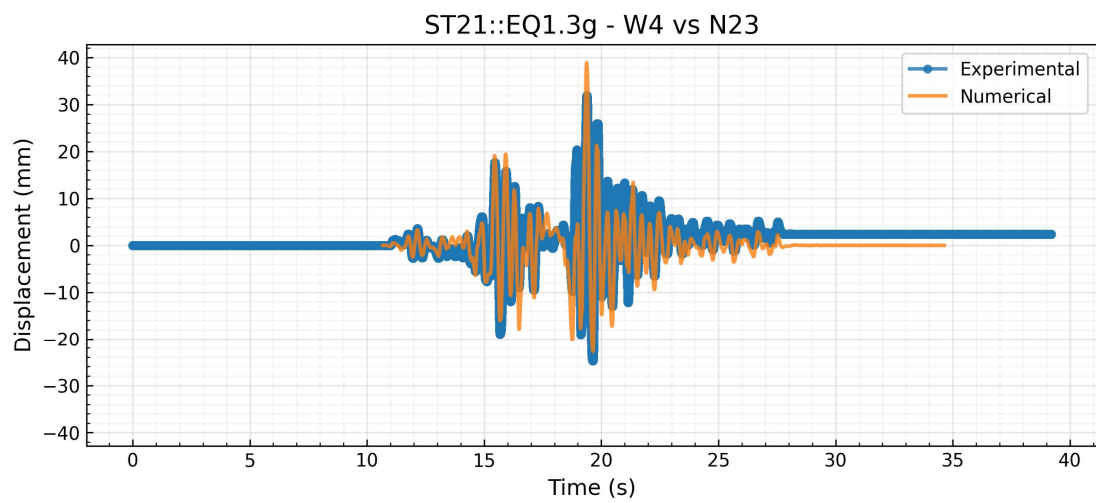


Figure 293 ST21 - Displacement comparison W4 vs N23

6.12 ST22::WNB1.3G(2) RESULTS

The result for draw-wires for ST22::WNB1.3g(2) are presented here.

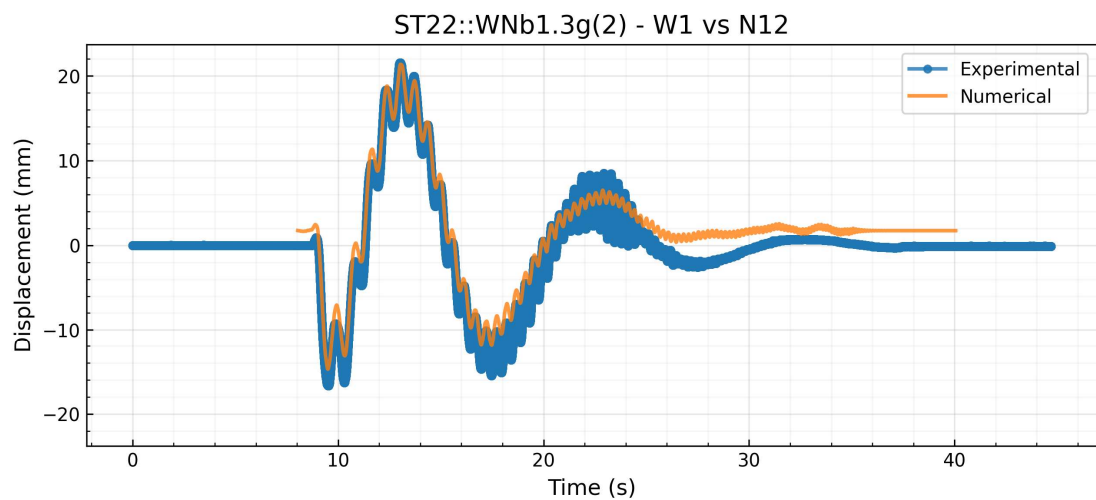


Figure 294 ST22 - Displacement comparison W1 vs N12

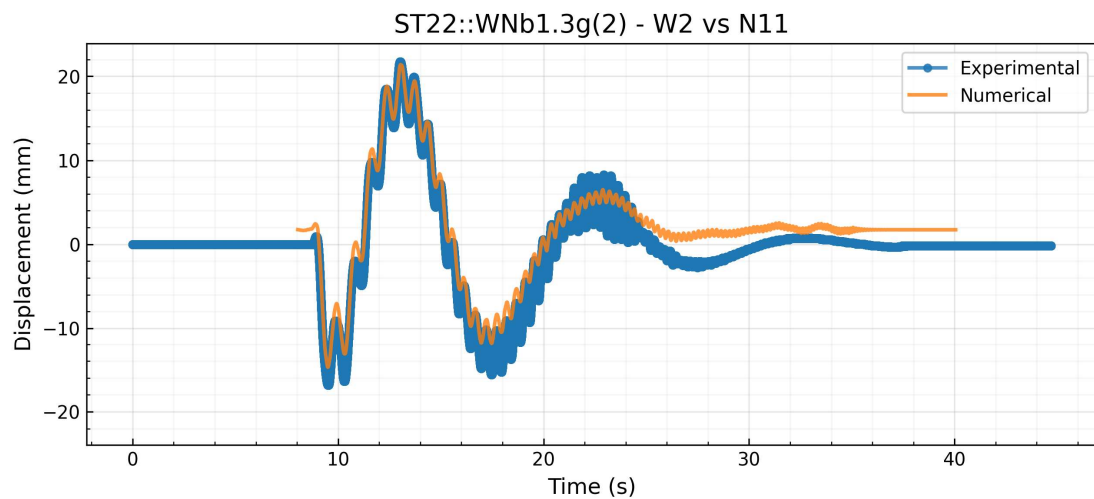


Figure 295 ST22 - Displacement comparison W2 vs N11

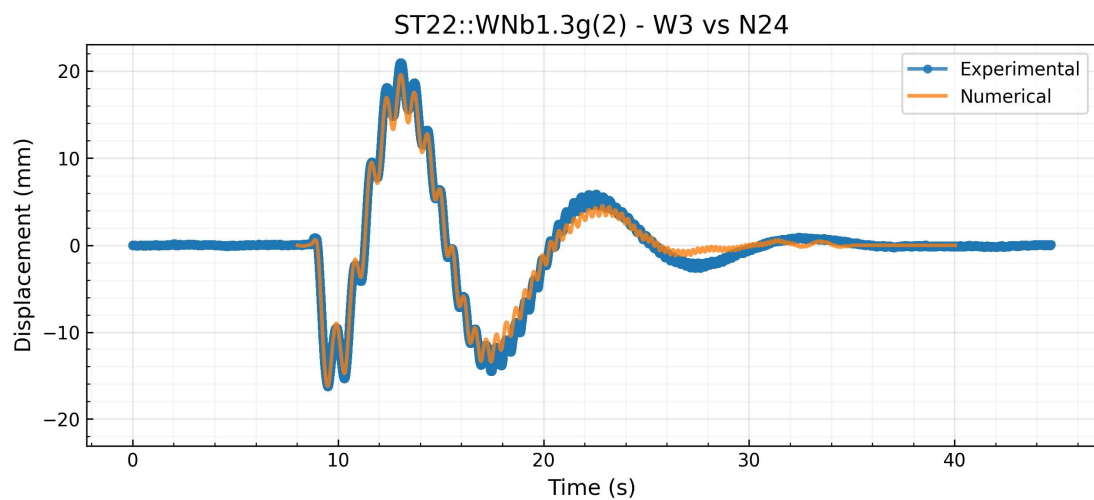


Figure 296 ST22 - Displacement comparison W3 vs N24

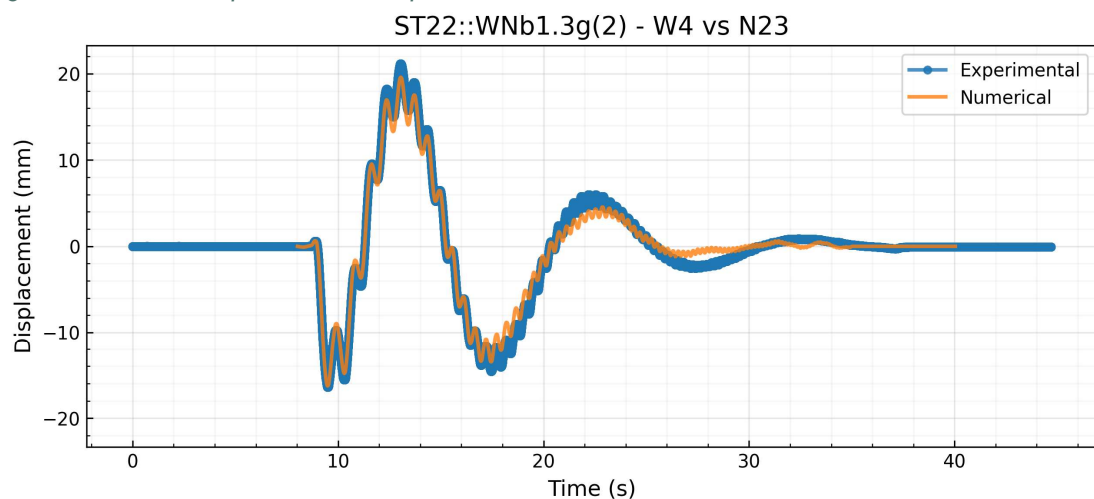


Figure 297 ST22 - Displacement comparison W4 vs N23

6.13 ST23::EQ1.3G(2) RESULTS

The result for draw-wires and accelerometers for ST23::EQ1.3g(2) are presented here.

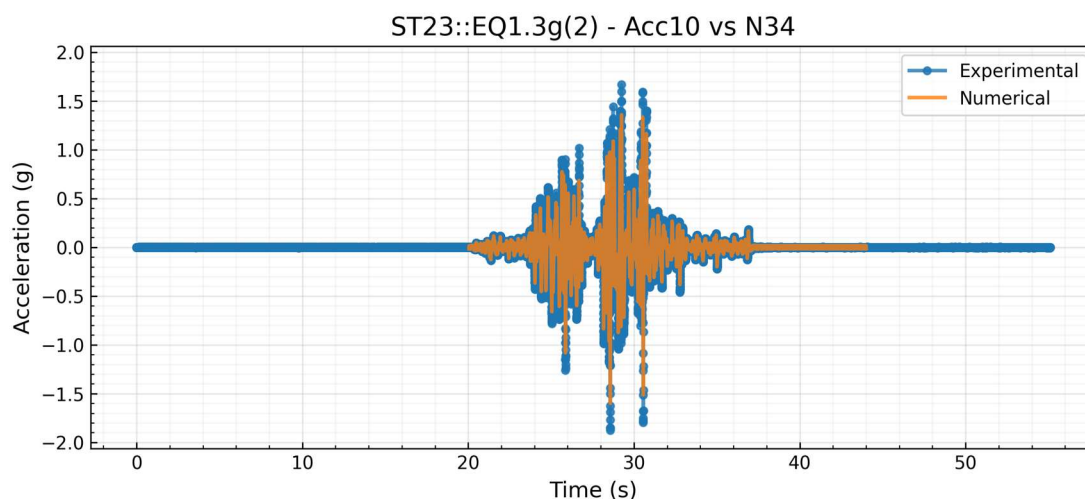


Figure 298 ST23 - Acceleration comparison Acc10 vs N34

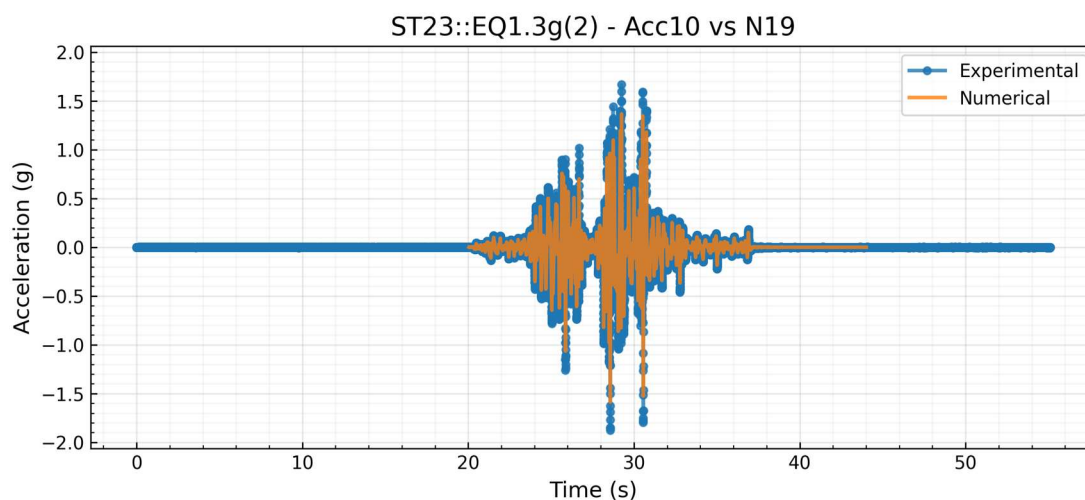


Figure 299 ST23 - Acceleration comparison Acc10 vs N19

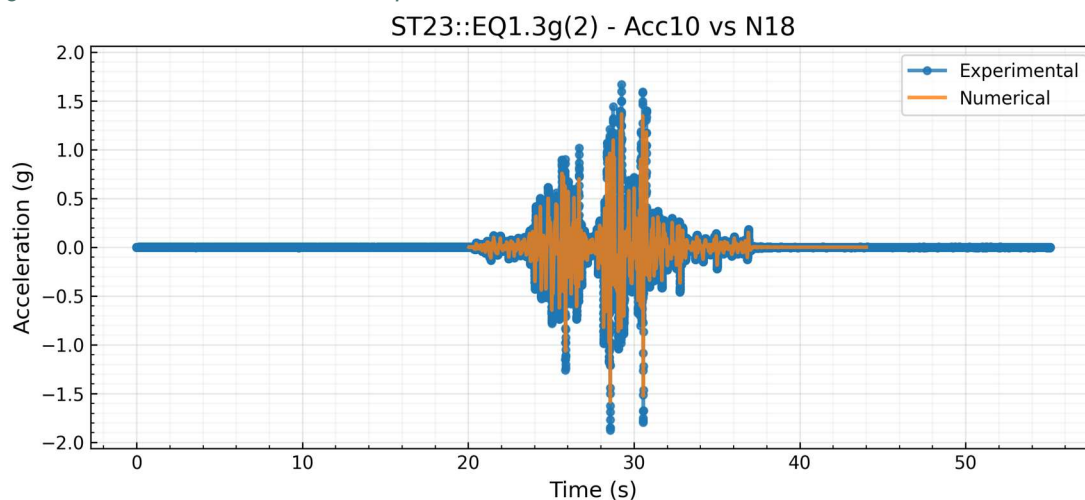


Figure 300 ST23 - Acceleration comparison Acc10 vs N18

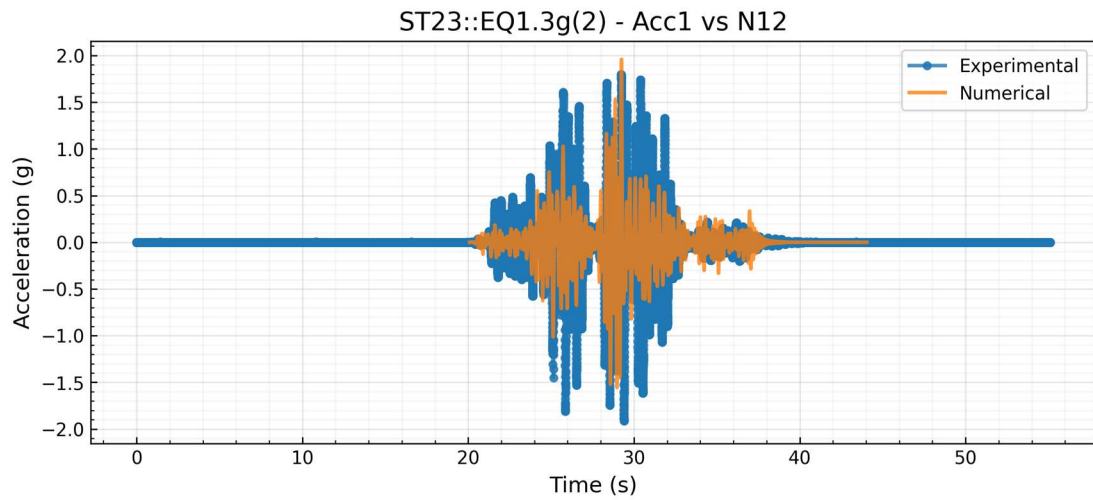


Figure 301 ST23 - Acceleration comparison Acc1 vs N12

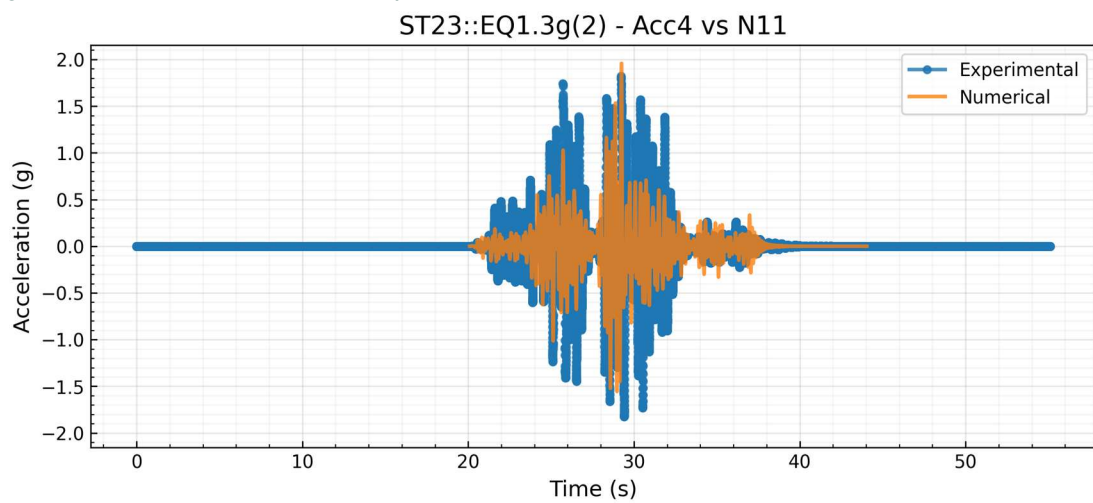


Figure 302 ST23 - Acceleration comparison Acc4 vs N11

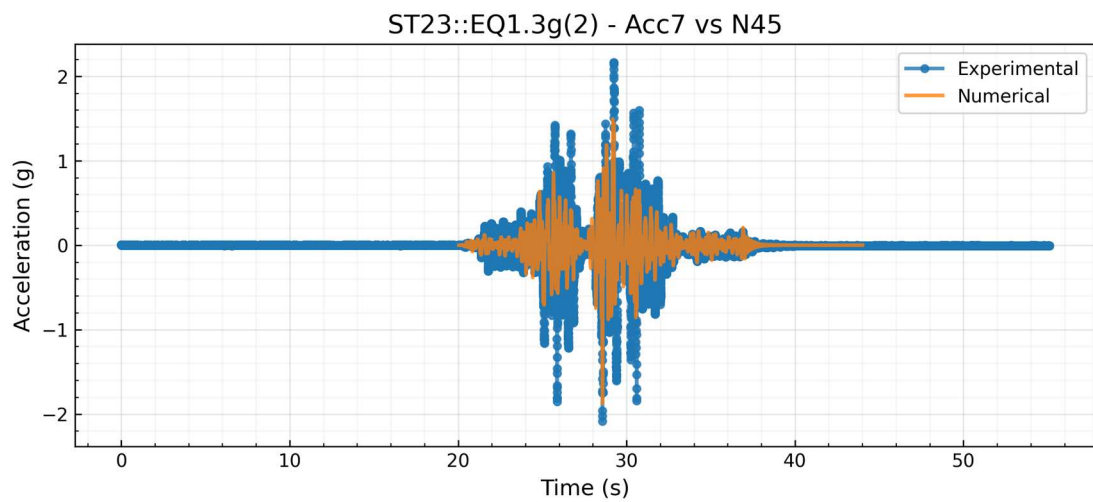


Figure 303 ST23 - Acceleration comparison Acc7 vs N45

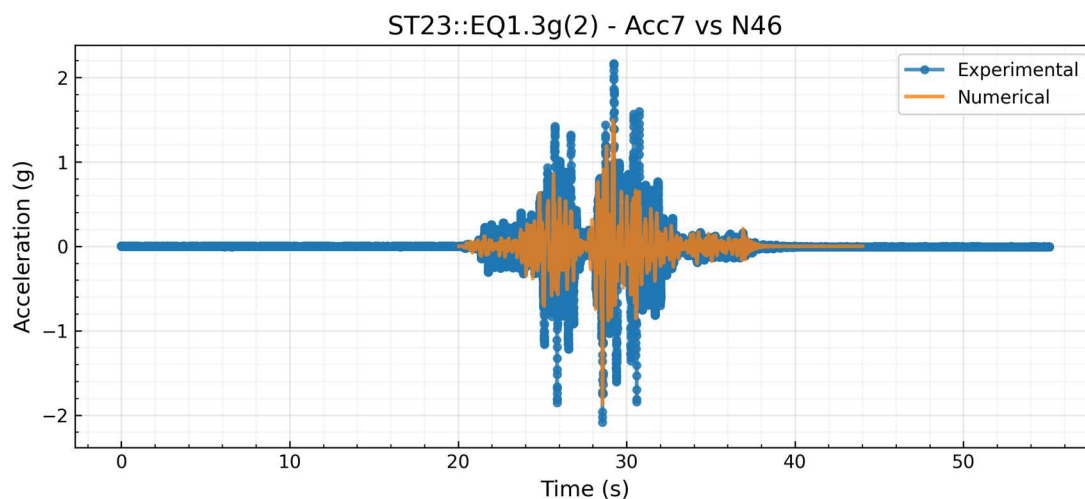


Figure 304 ST23 - Acceleration comparison Acc7 vs N46

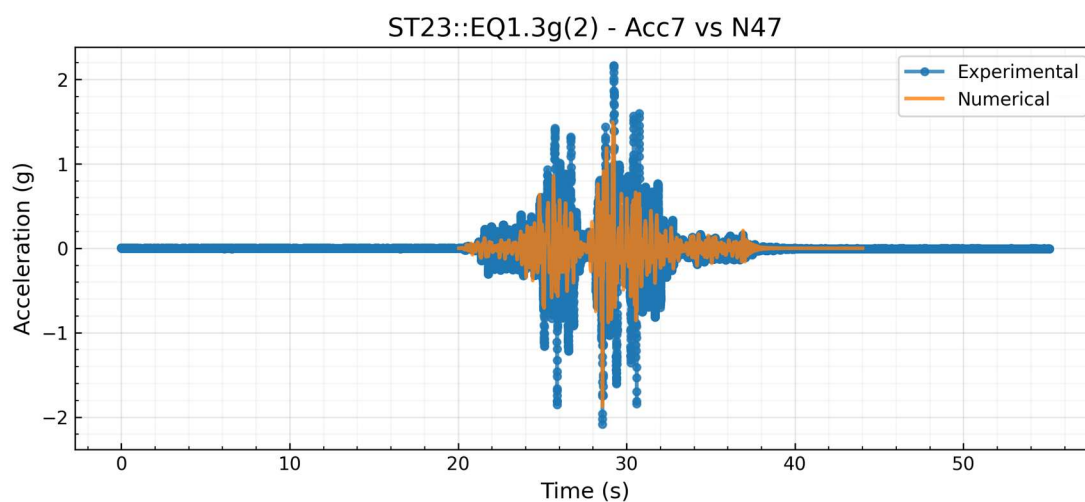


Figure 305 ST23 - Acceleration comparison Acc7 vs N47

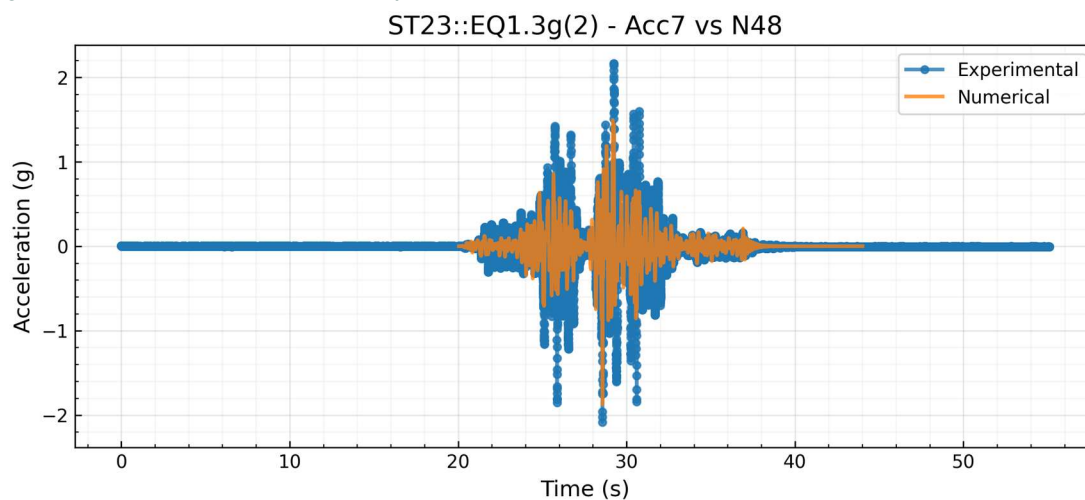


Figure 306 ST23 - Acceleration comparison Acc7 vs N48

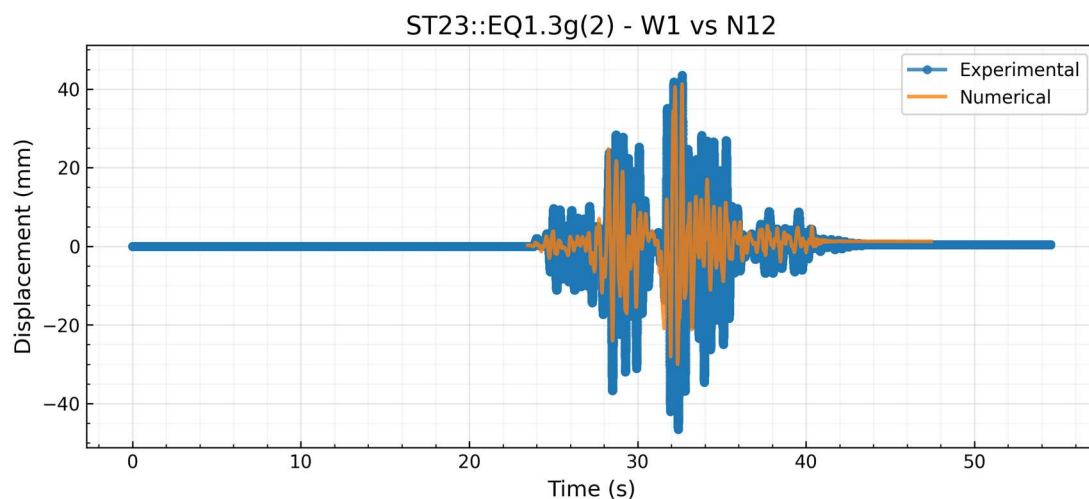


Figure 307 ST23 - Displacement comparison W1 vs N12

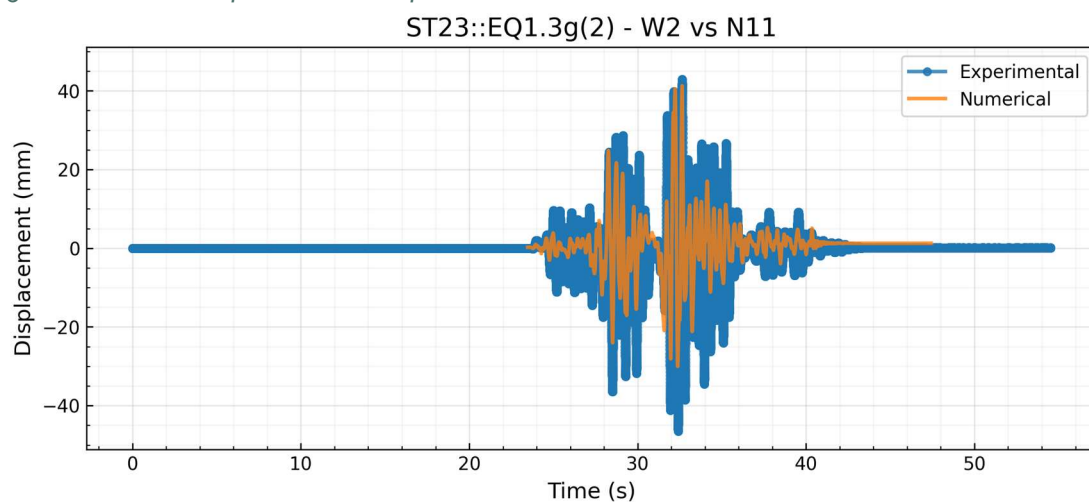


Figure 308 ST23 - Displacement comparison W2 vs N11

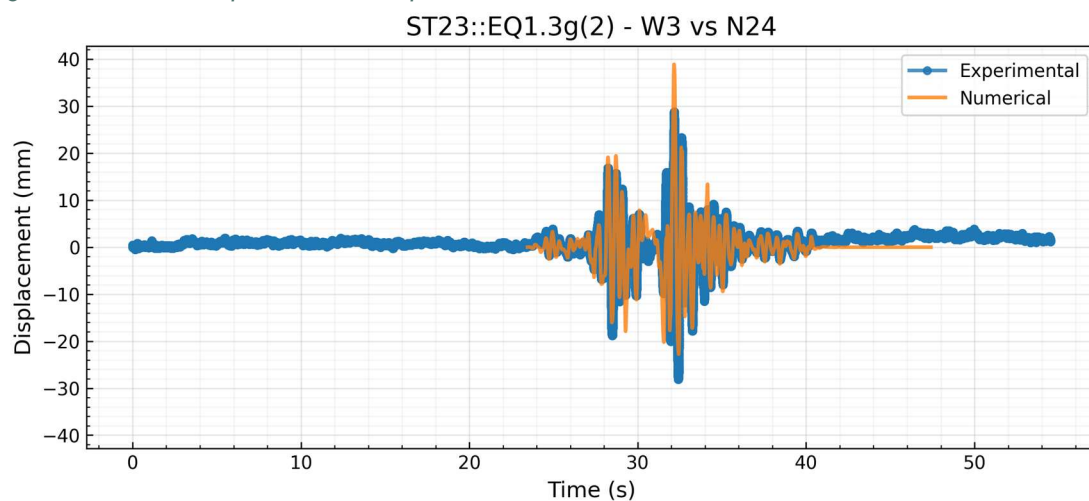


Figure 309 ST23 - Displacement comparison W3 vs N24

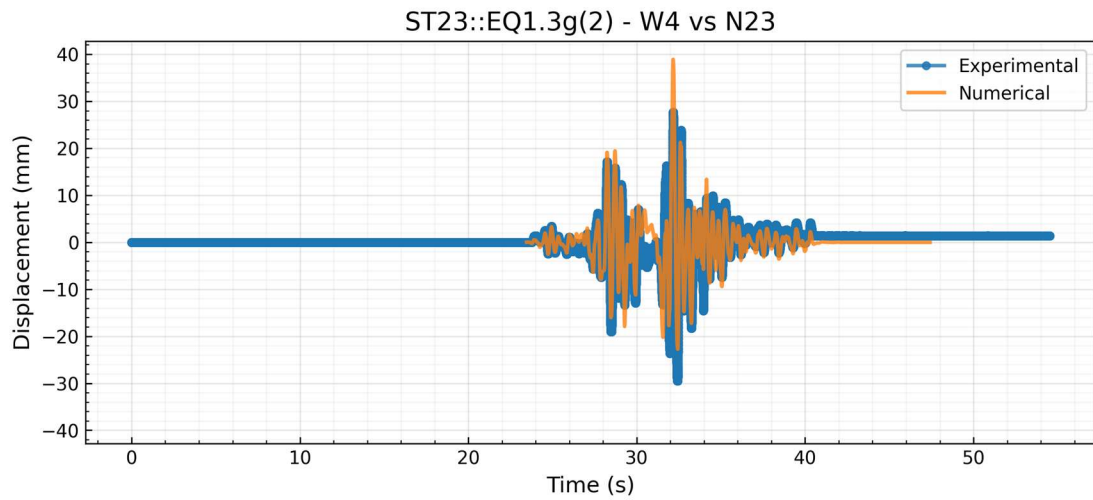


Figure 310 ST23 - Displacement comparison W4 vs N23

6.14 ST25::EQ1.4G RESULTS

The result for draw-wires and accelerometers for ST25::EQ1.4g are presented here.

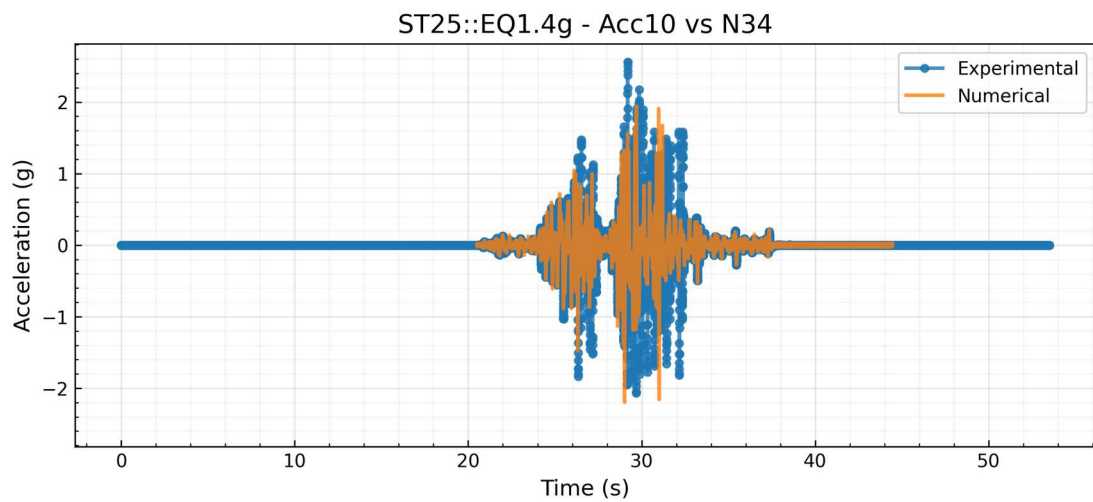


Figure 311 ST25 - Acceleration comparison Acc10 vs N34

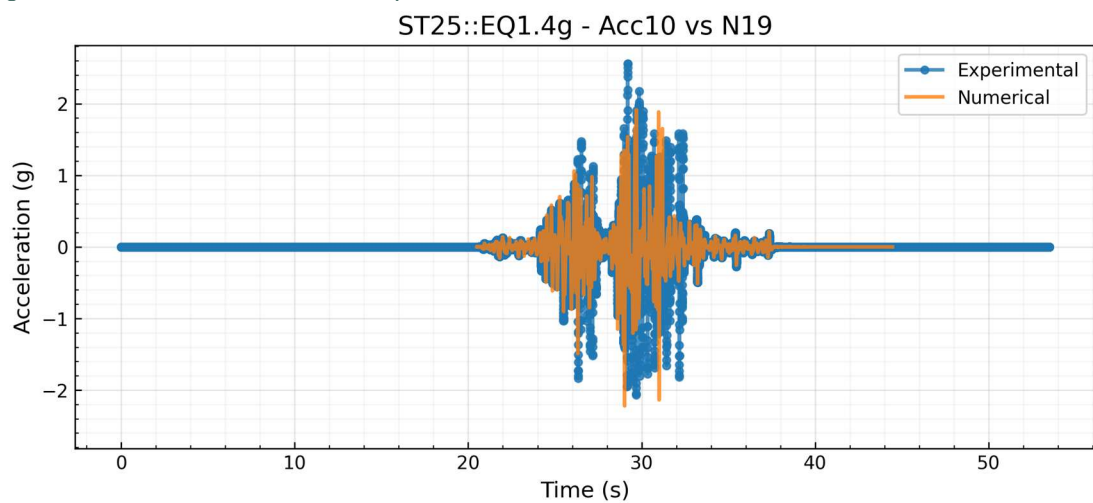


Figure 312 ST25 - Acceleration comparison Acc10 vs N19

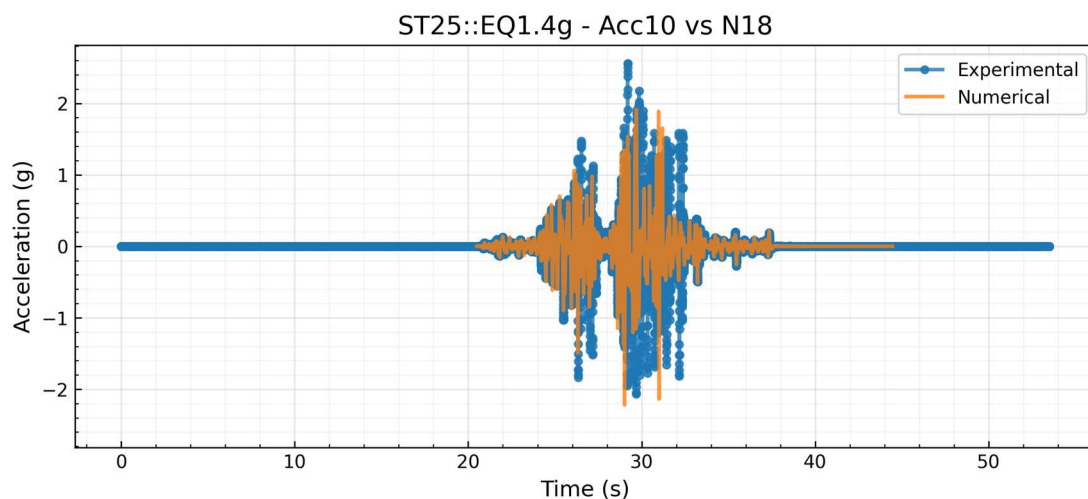


Figure 313 ST25 - Acceleration comparison Acc10 vs N18

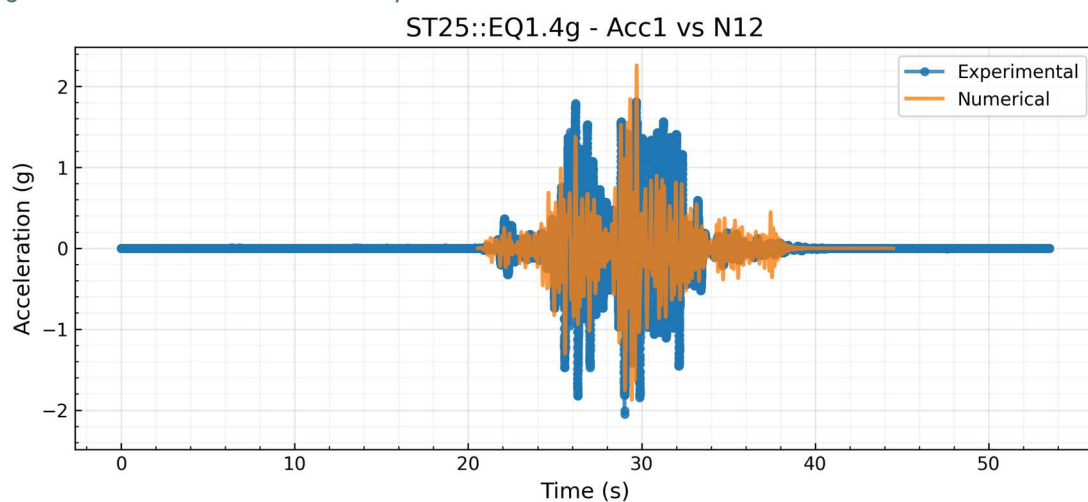


Figure 314 ST25 - Acceleration comparison Acc1 vs N12

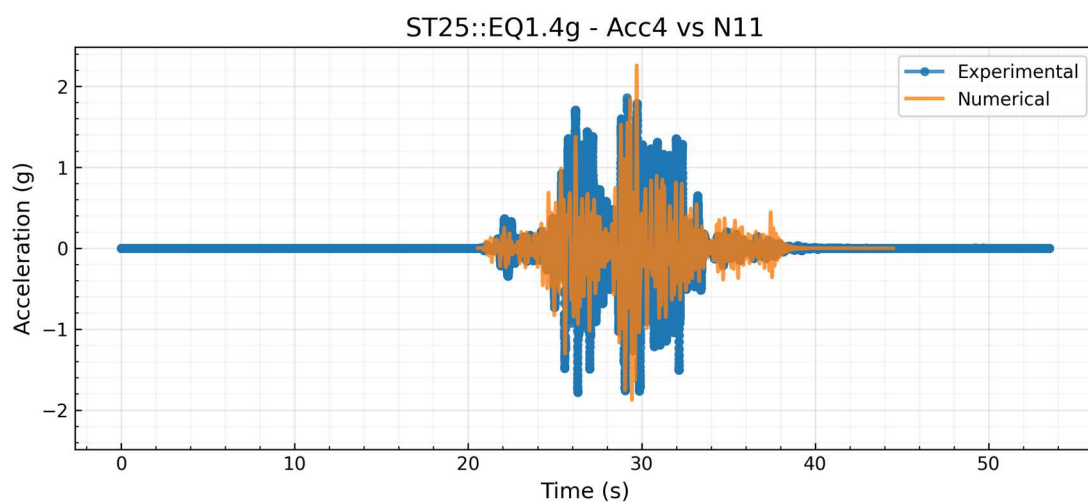


Figure 315 ST25 - Acceleration comparison Acc4 vs N11

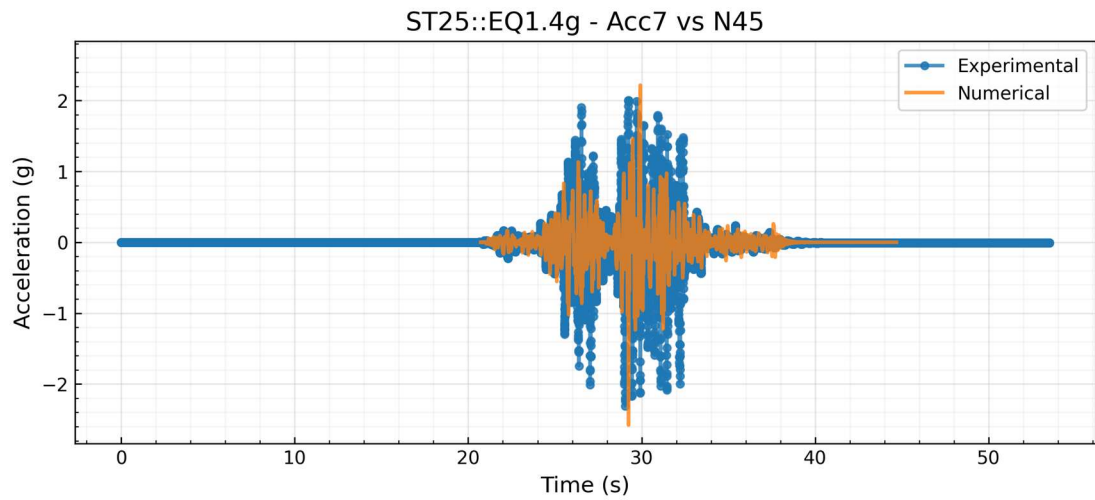


Figure 316 ST25 - Acceleration comparison Acc7 vs N45

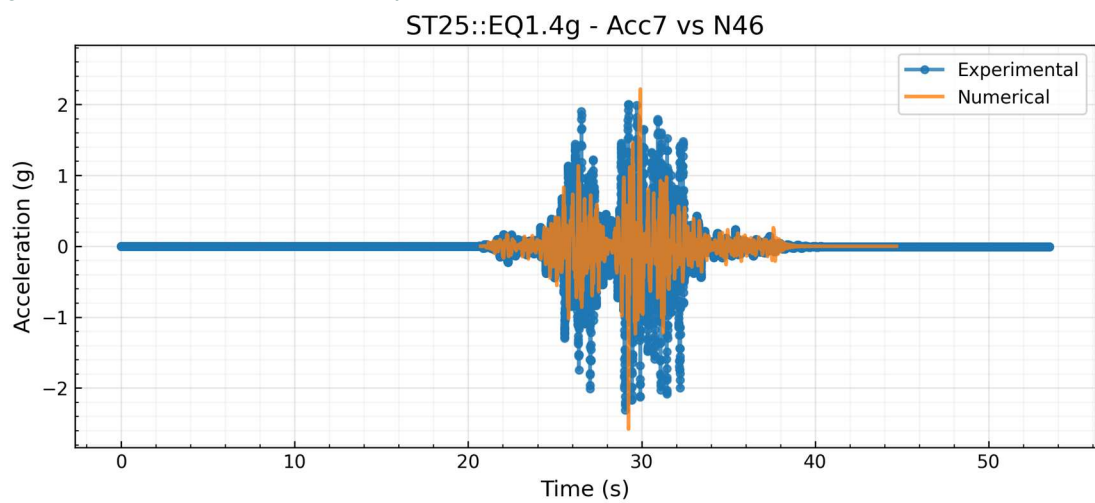


Figure 317 ST25 - Acceleration comparison Acc7 vs N46

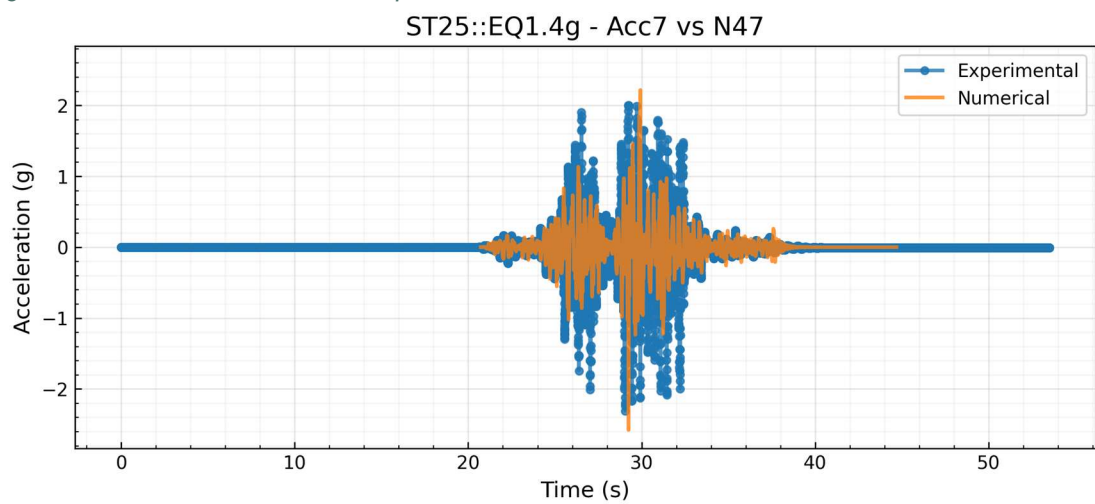


Figure 318 ST25 - Acceleration comparison Acc7 vs N47

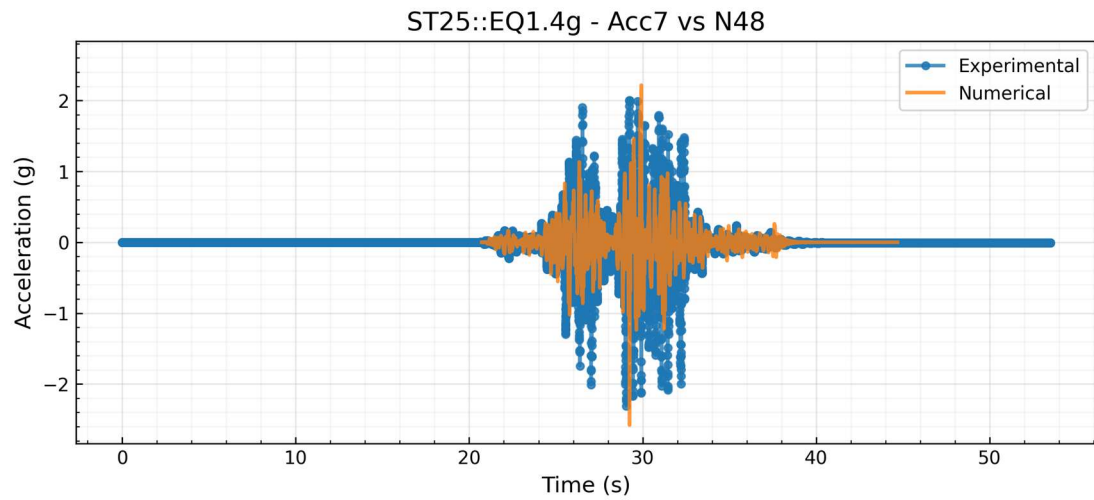


Figure 319 ST25 - Acceleration comparison Acc7 vs N48

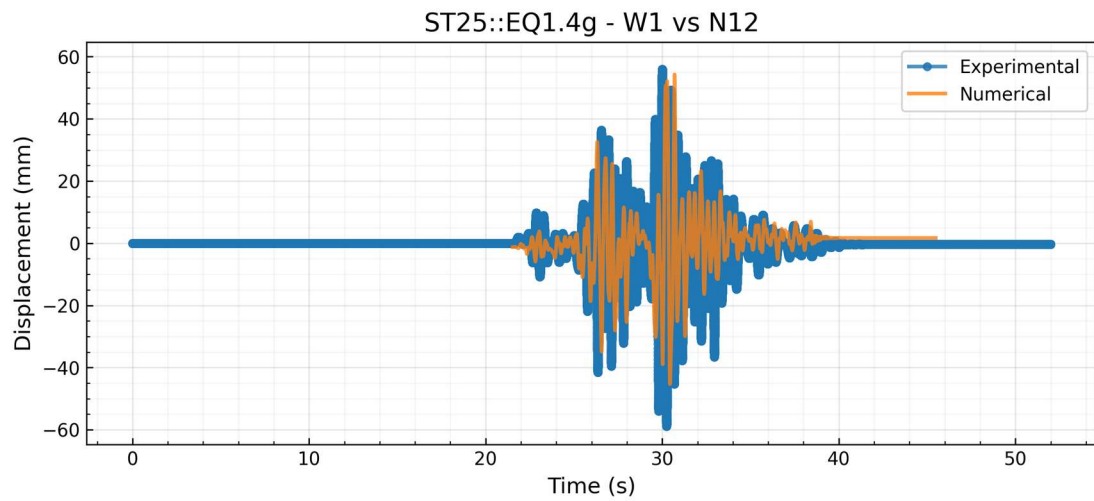


Figure 320 ST25 - Displacement comparison W1 vs N12

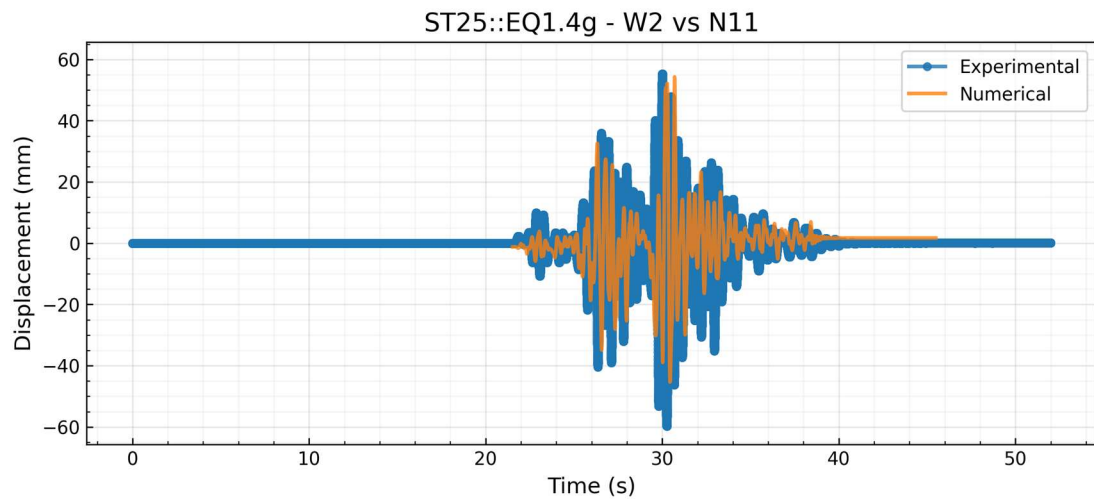


Figure 321 ST25 - Displacement comparison W2 vs N11

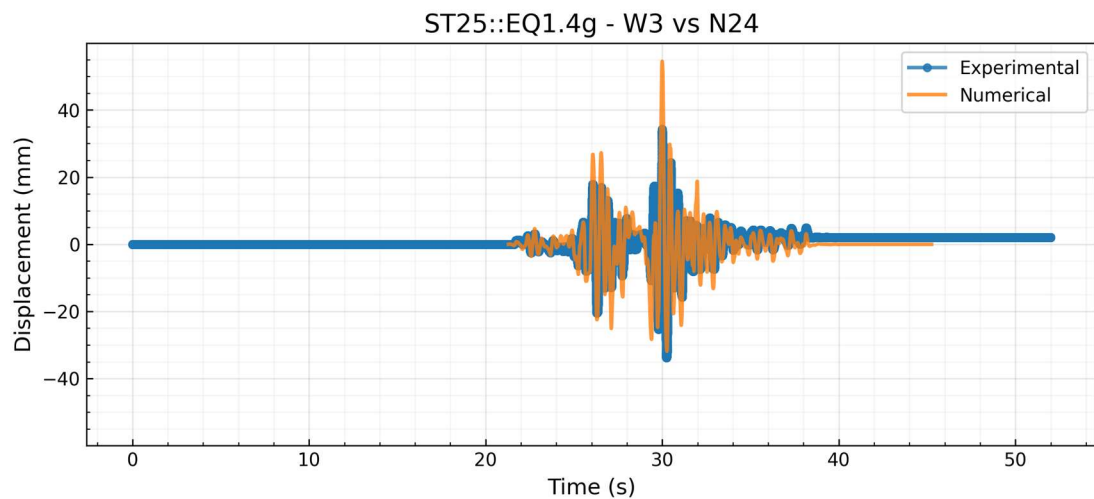


Figure 322 ST25 - Displacement comparison W3 vs N24

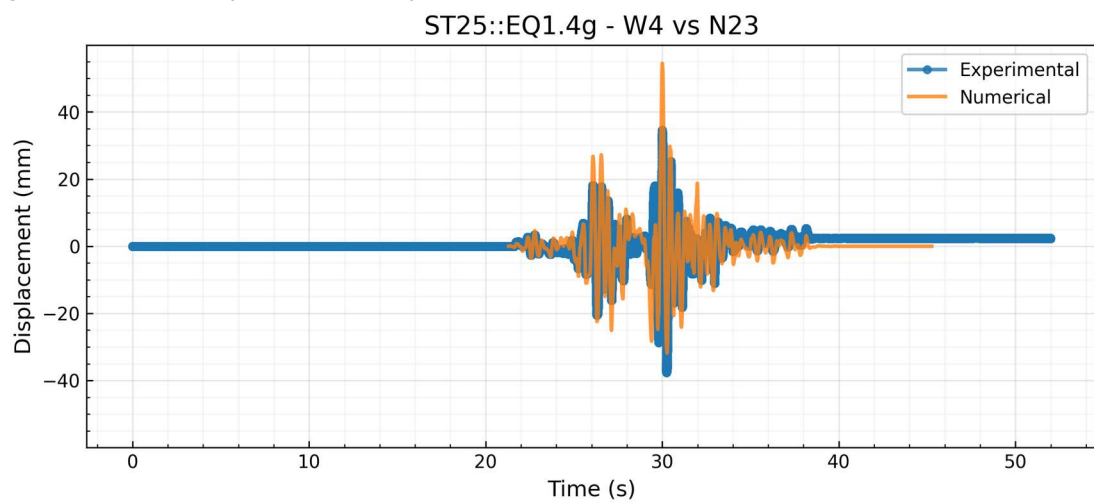


Figure 323 ST25 - Displacement comparison W4 vs N23

6.15 ST27::EQ0.2G (2) RESULTS

The result for draw-wires and accelerometers for ST27::EQ0.2g (2) are presented here.

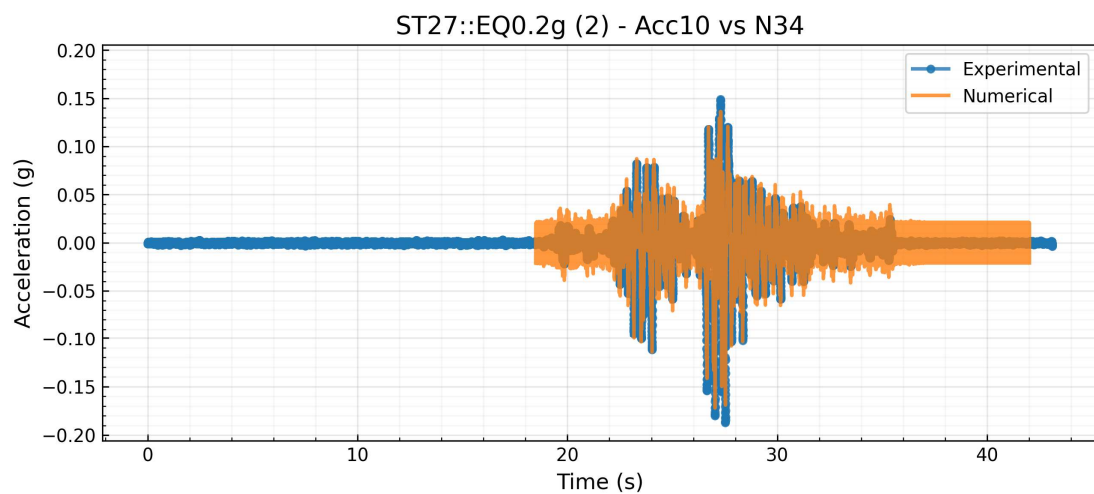


Figure 324 ST27 - Acceleration comparison Acc10 vs N34

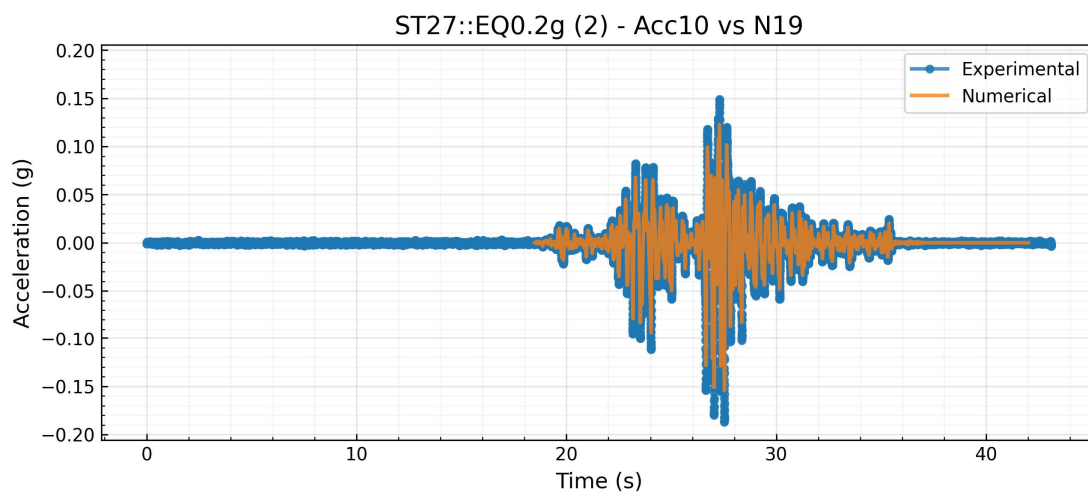


Figure 325 ST27 - Acceleration comparison Acc10 vs N19

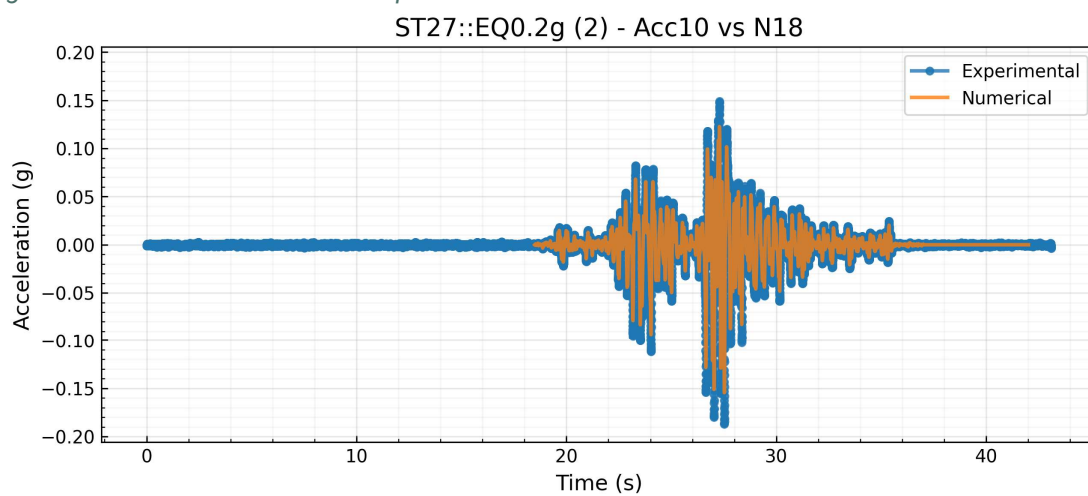


Figure 326 ST27 - Acceleration comparison Acc10 vs N18

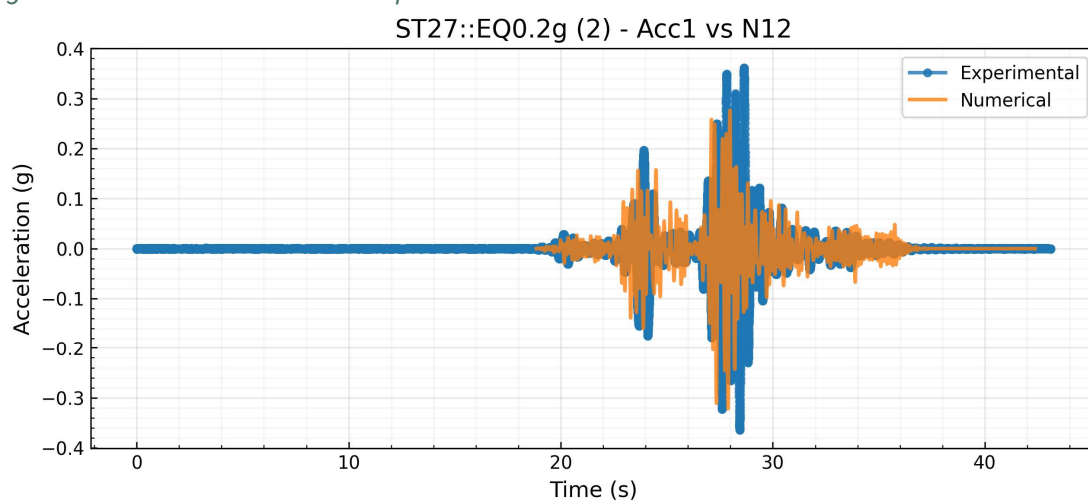


Figure 327 ST27 - Acceleration comparison Acc1 vs N12

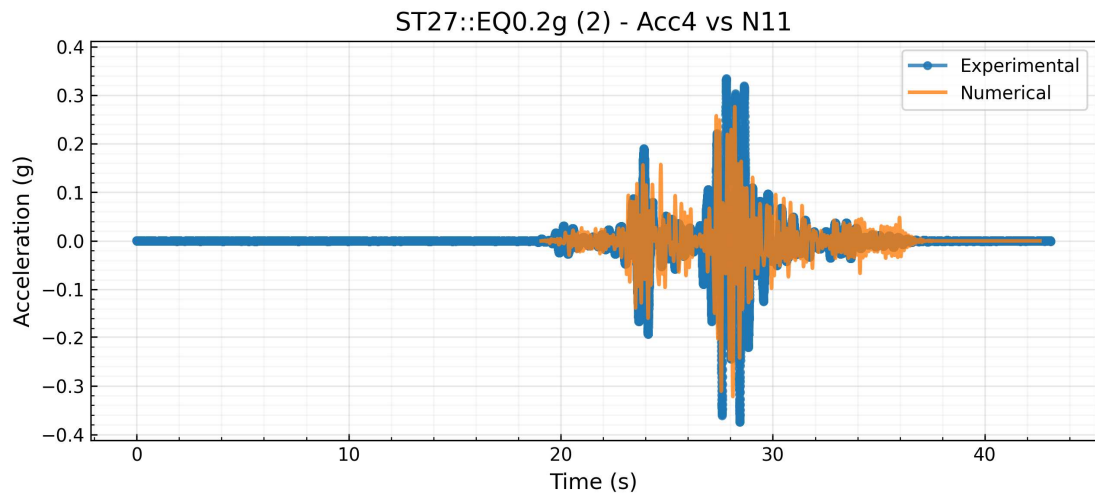


Figure 328 ST27 - Acceleration comparison Acc4 vs N11

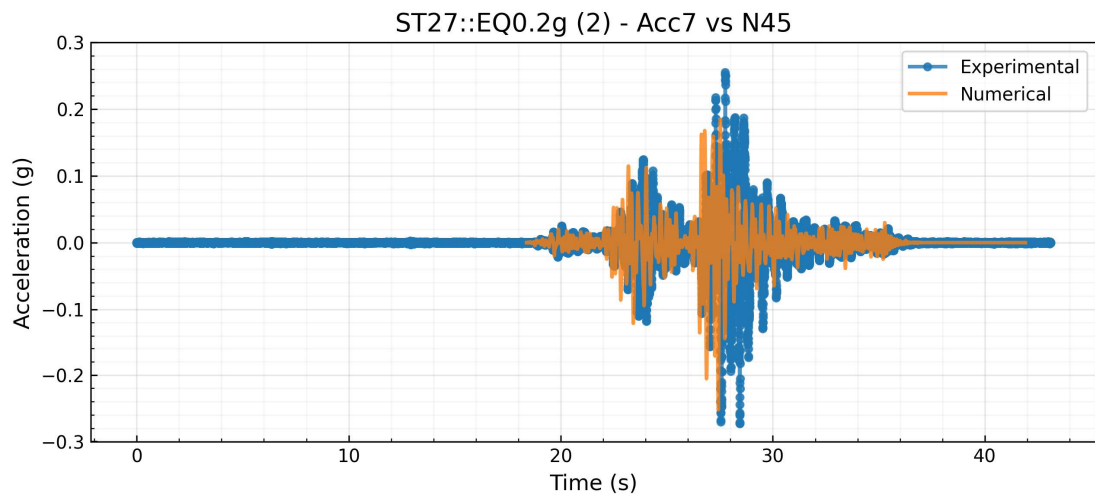


Figure 329 ST27 - Acceleration comparison Acc7 vs N45

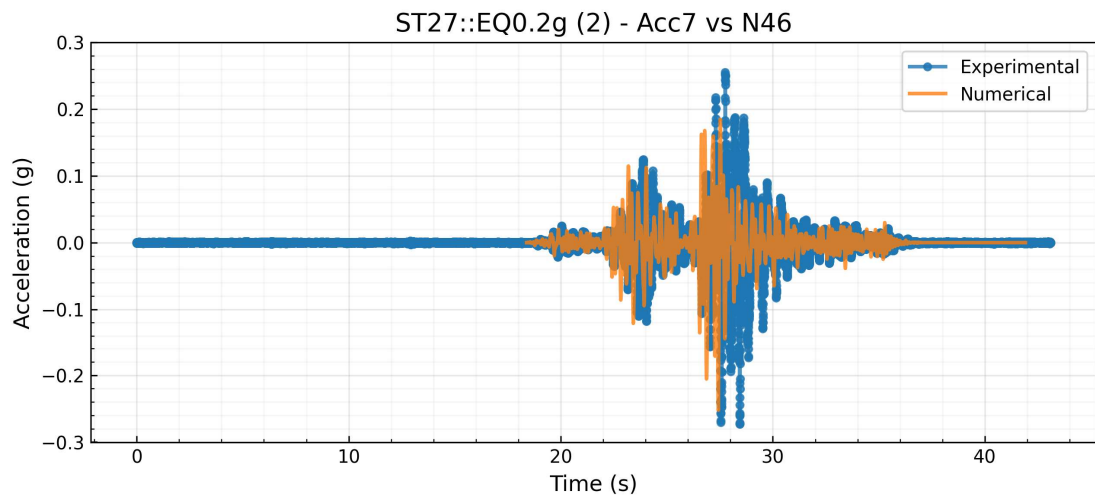


Figure 330 ST27 - Acceleration comparison Acc7 vs N46

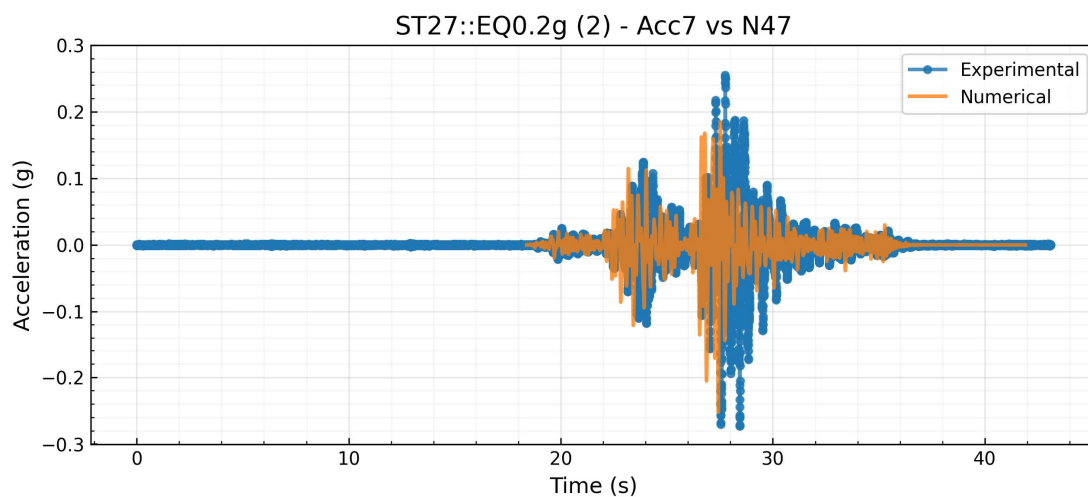


Figure 331 ST27 - Acceleration comparison Acc7 vs N47

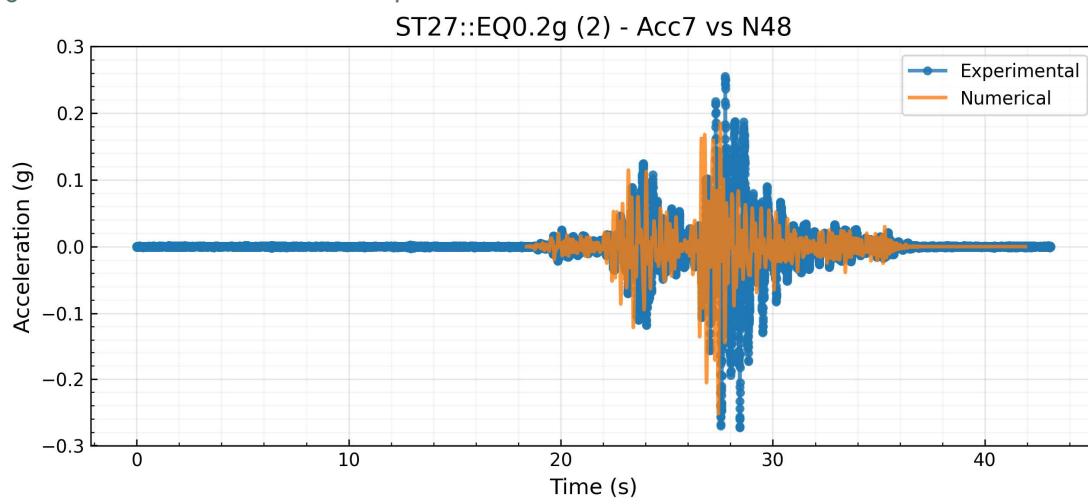


Figure 332 ST27 - Acceleration comparison Acc7 vs N48

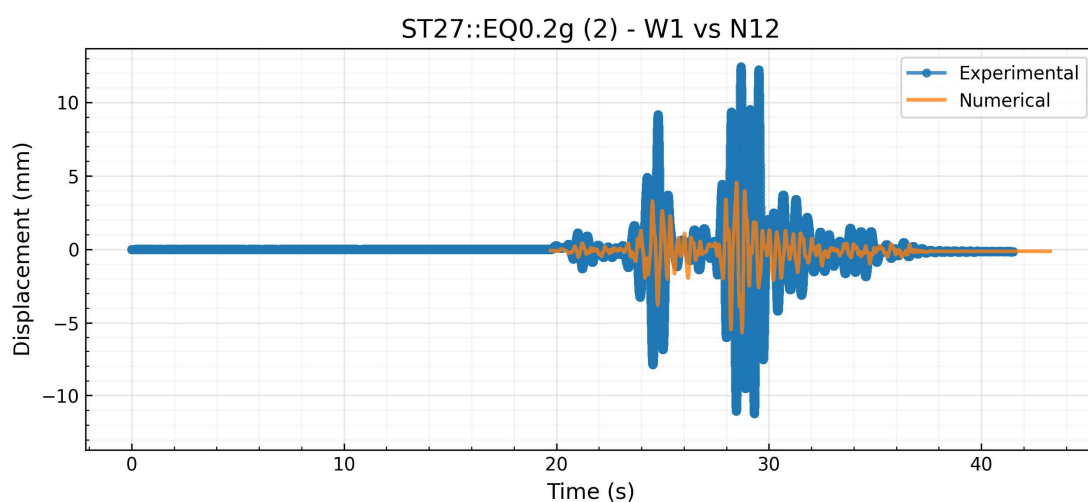


Figure 333 ST27 - Displacement comparison W1 vs N12

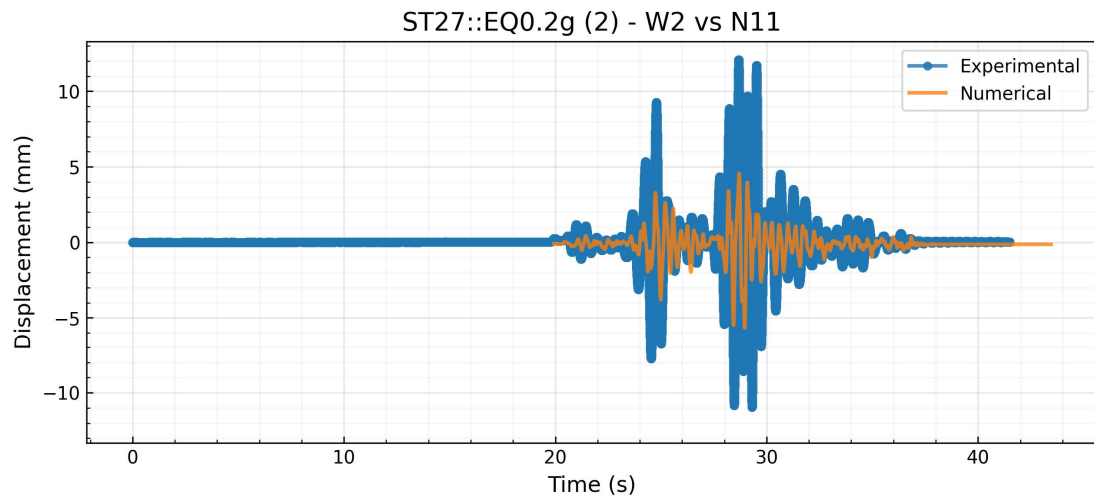


Figure 334 ST27 - Displacement comparison W2 vs N11

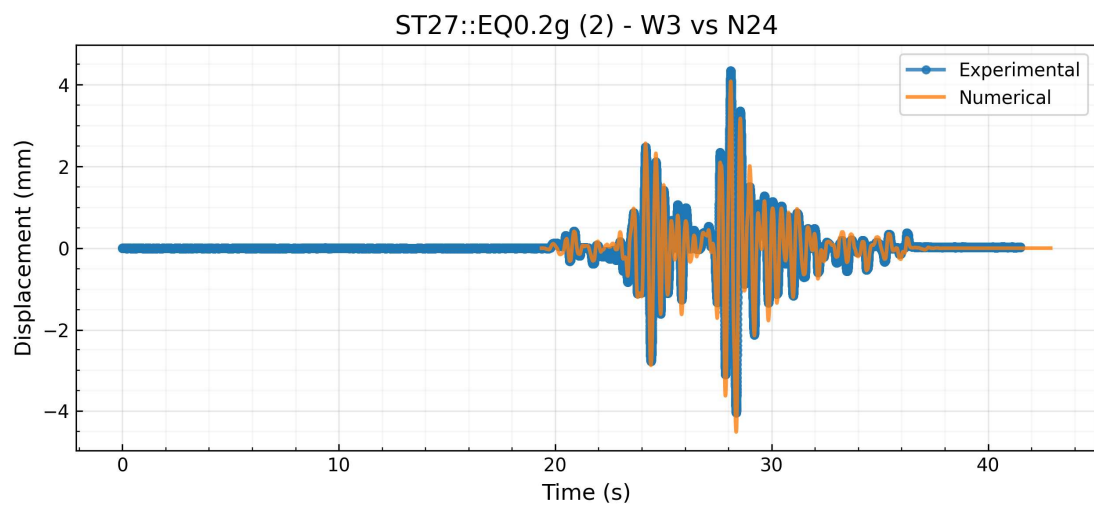


Figure 335 ST27 - Displacement comparison W3 vs N24

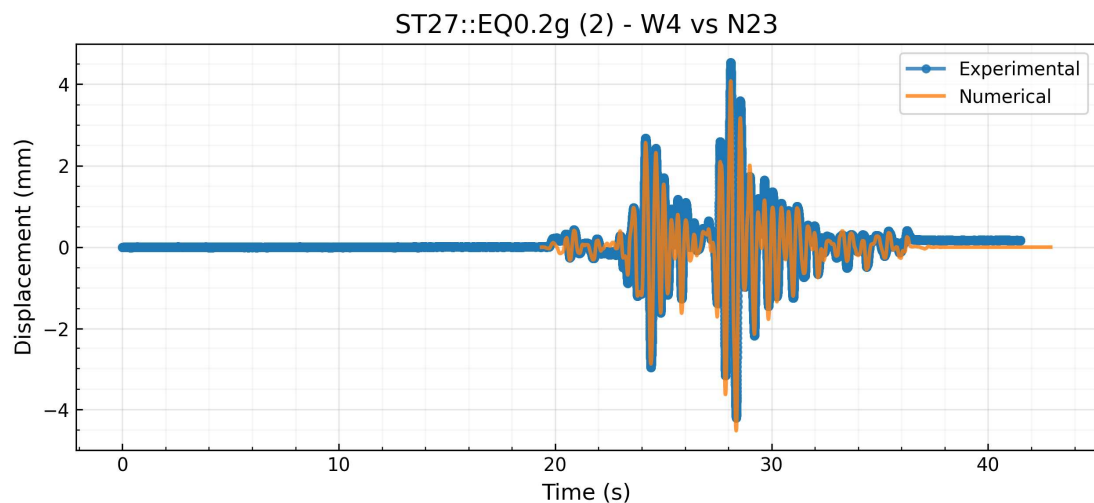


Figure 336 ST27 - Displacement comparison W4 vs N23

6.16 ST1::WNB0.07G (WITHOUT) RESULTS

The result for draw-wires and accelerometers for ST1::WNB0.07g (WITHOUT) are presented here.

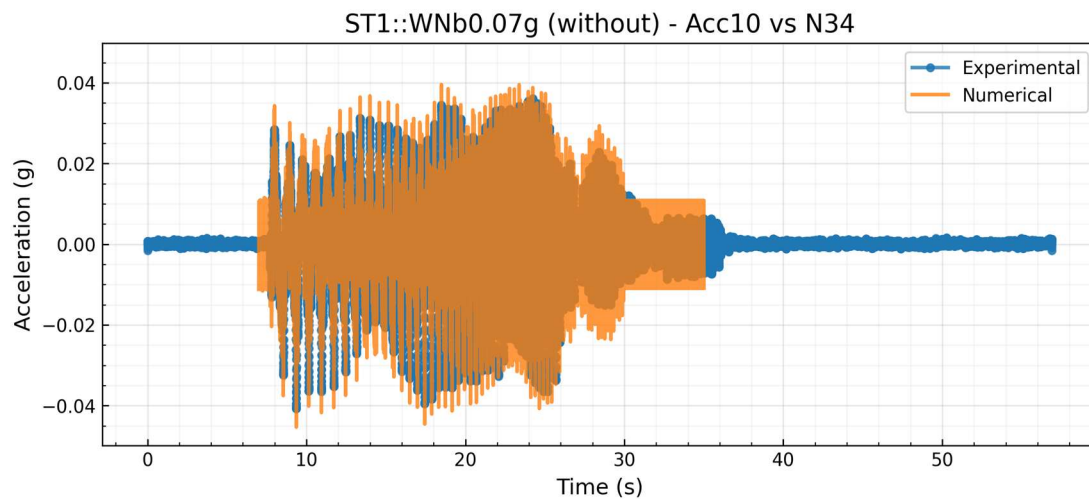


Figure 337 ST1 - Acceleration comparison Acc10 vs N34

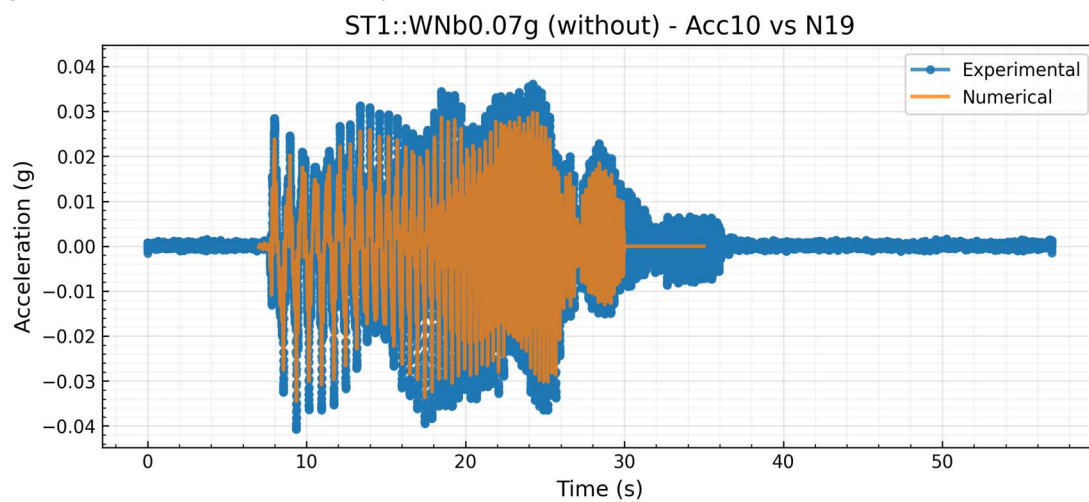


Figure 338 ST1 - Acceleration comparison Acc10 vs N19

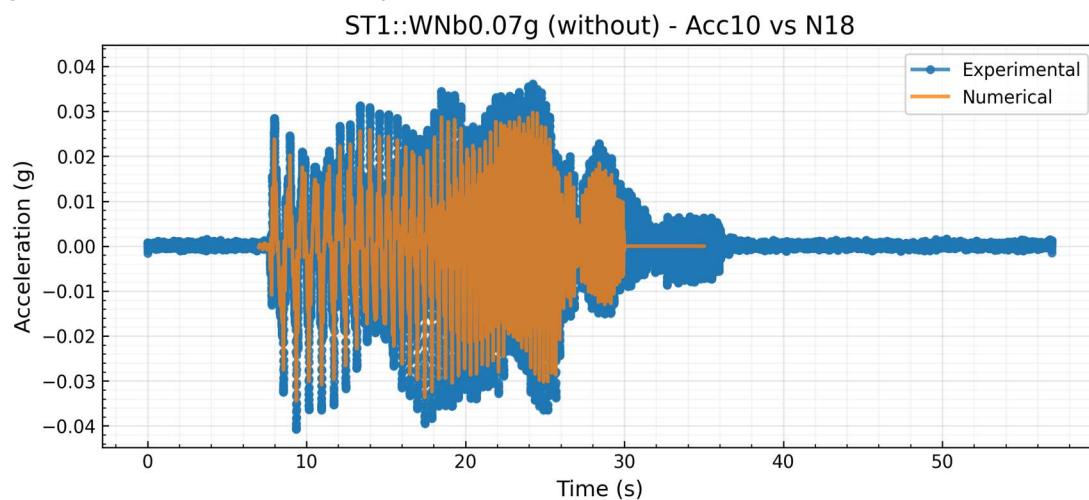


Figure 339 ST1 - Acceleration comparison Acc10 vs N18

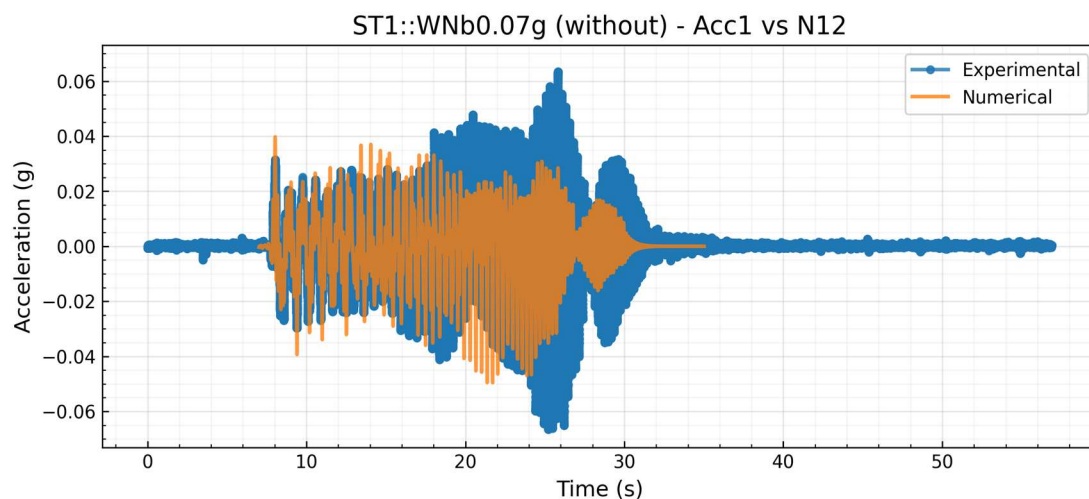


Figure 340 ST1 - Acceleration comparison Acc1 vs N12

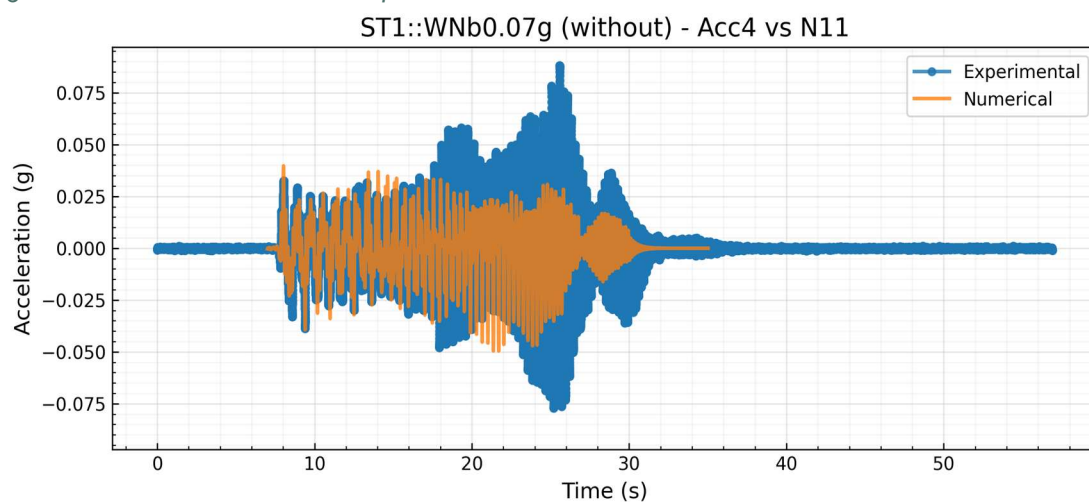


Figure 341 ST1 - Acceleration comparison Acc4 vs N11

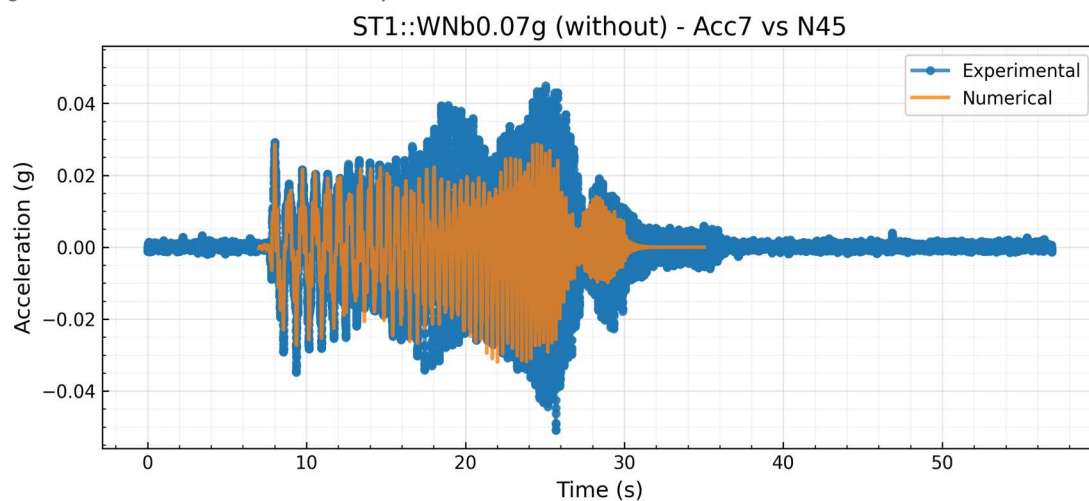


Figure 342 ST1 - Acceleration comparison Acc7 vs N45

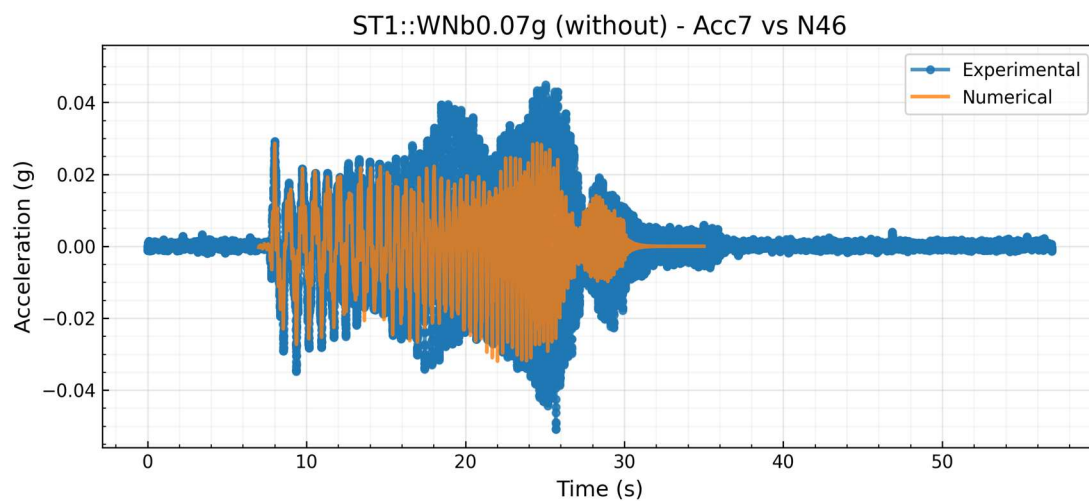


Figure 343 ST1 - Acceleration comparison Acc7 vs N46

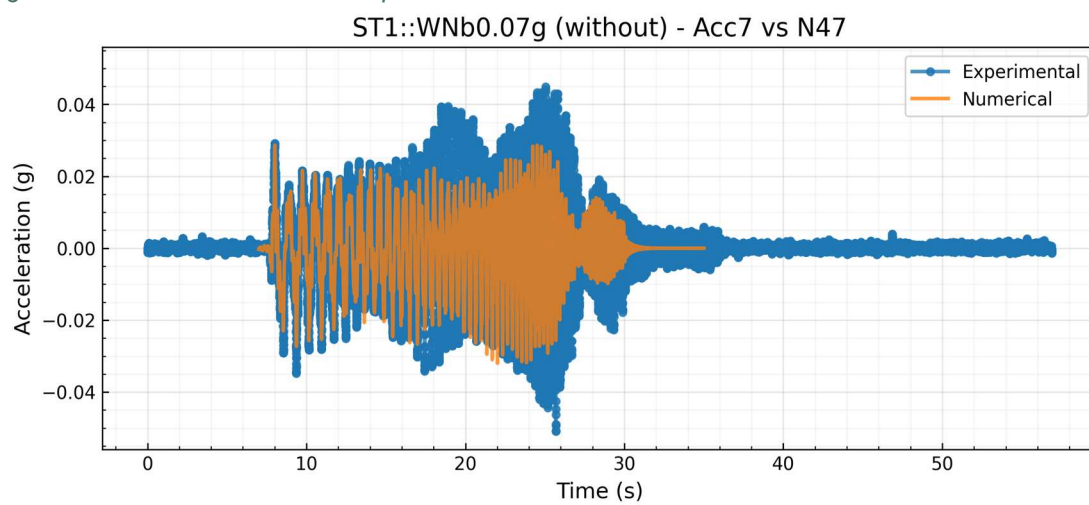


Figure 344 ST1 - Acceleration comparison Acc7 vs N47

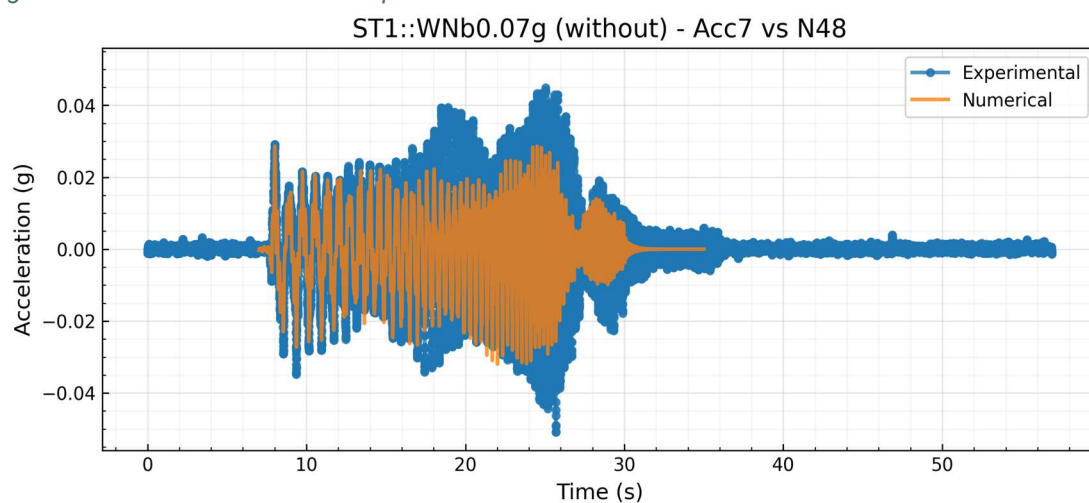


Figure 345 ST1 - Acceleration comparison Acc7 vs N48

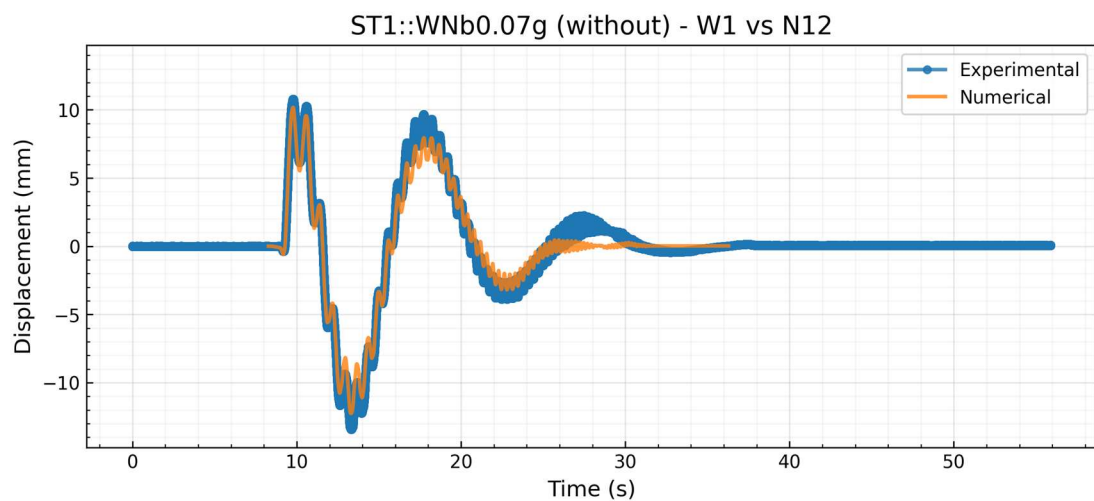


Figure 346 ST1 - Displacement comparison W1 vs N12

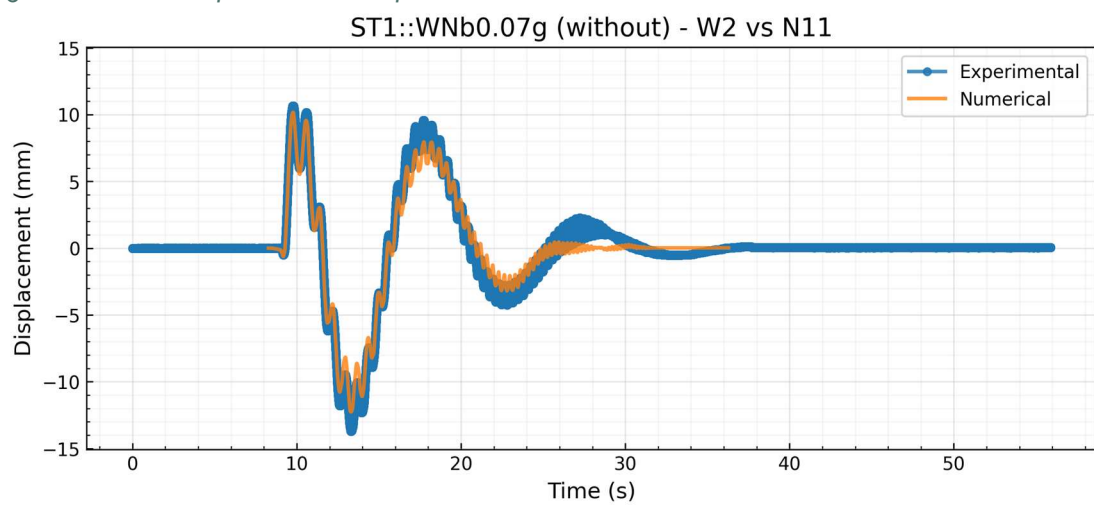


Figure 347 ST1 - Displacement comparison W2 vs N11

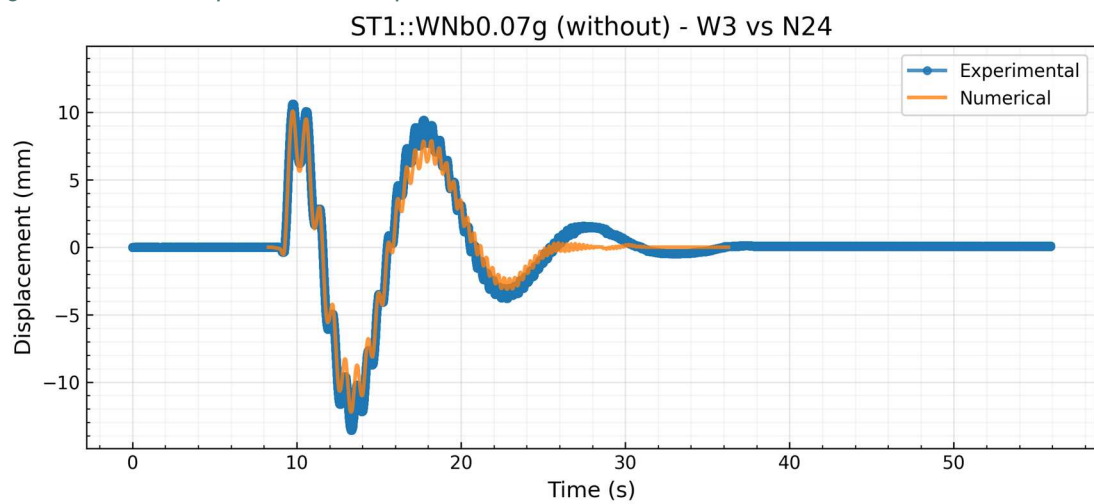


Figure 348 ST1 - Displacement comparison W3 vs N24

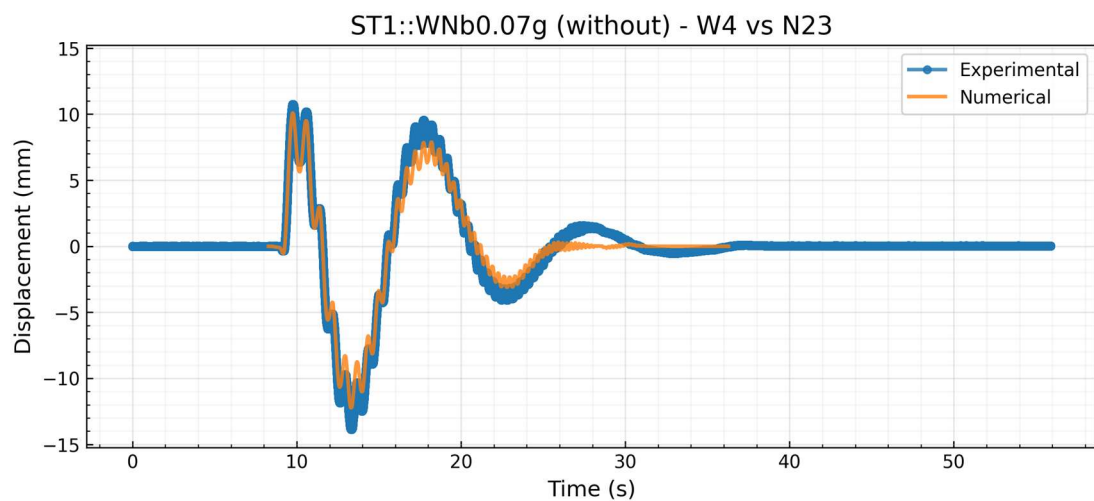


Figure 349 ST1 - Displacement comparison W4 vs N23

6.17 ST2::WNB0.07G RESULTS

The result for draw-wires and accelerometers for ST2::WNB0.07g are presented here.

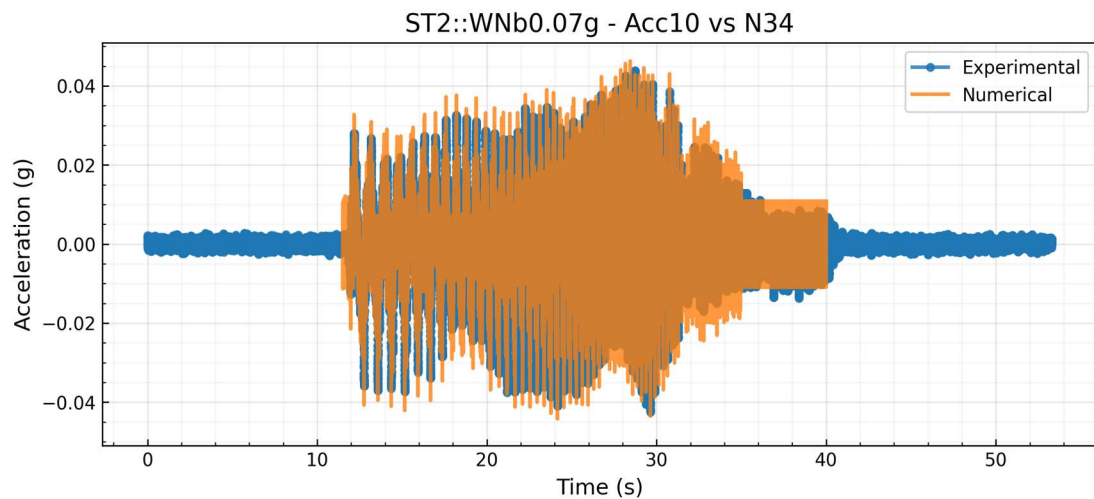


Figure 350 ST2 - Acceleration comparison Acc10 vs N34

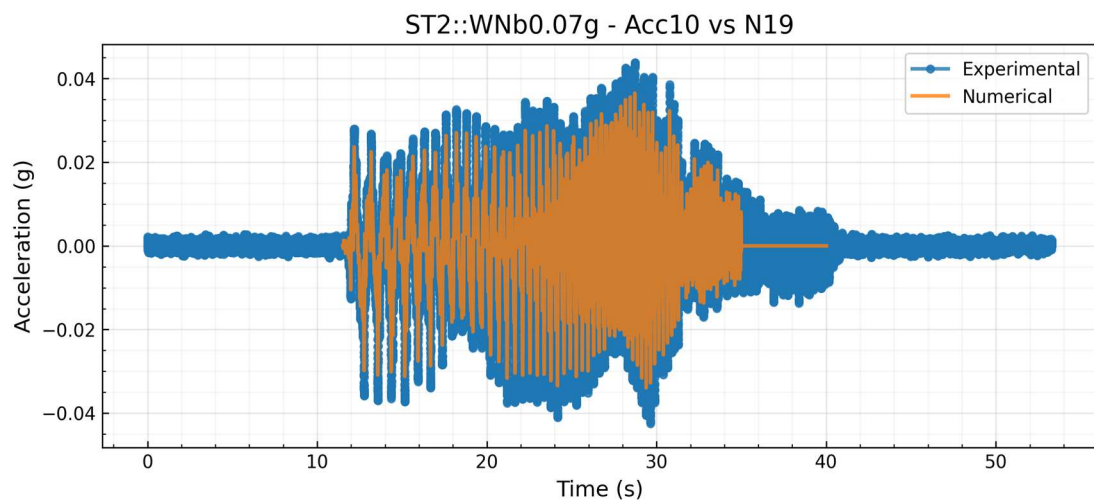


Figure 351 ST2 - Acceleration comparison Acc10 vs N19

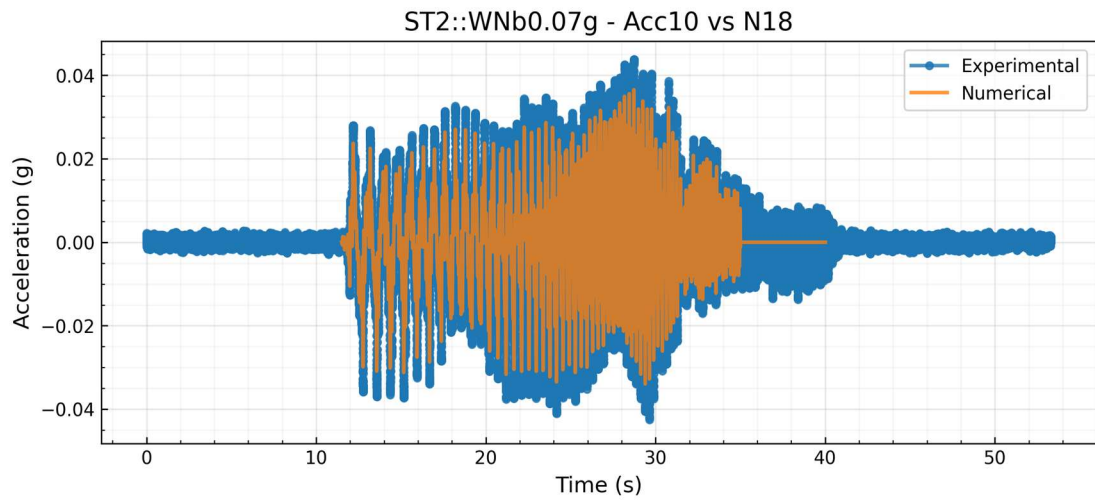


Figure 352 ST2 - Acceleration comparison Acc10 vs N18

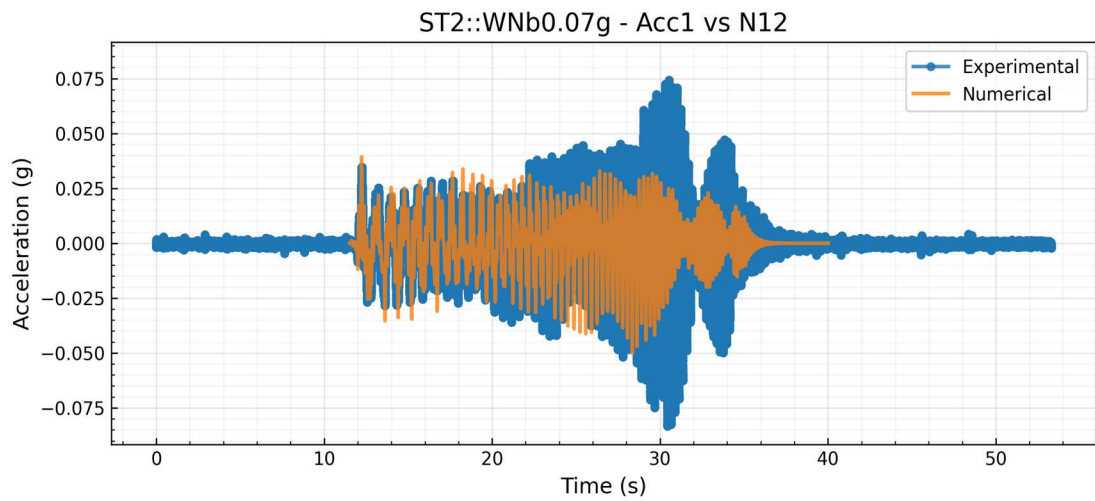


Figure 353 ST2 - Acceleration comparison Acc1 vs N12

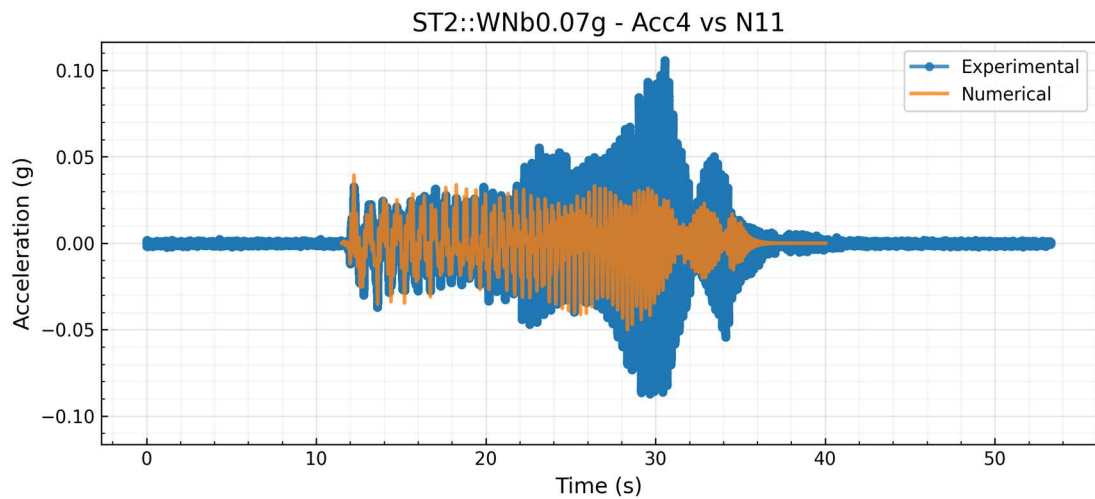


Figure 354 ST2 - Acceleration comparison Acc4 vs N11

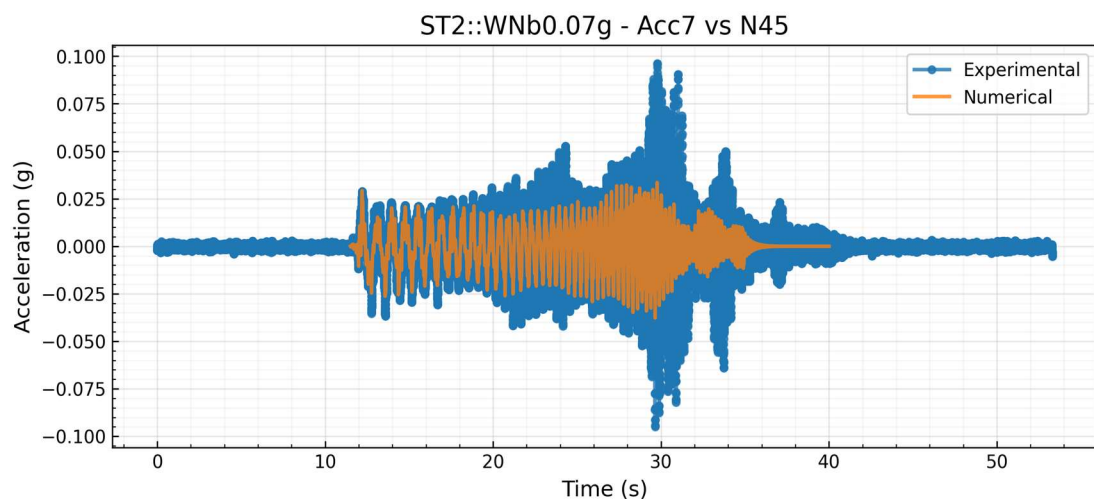


Figure 355 ST2 - Acceleration comparison Acc7 vs N45

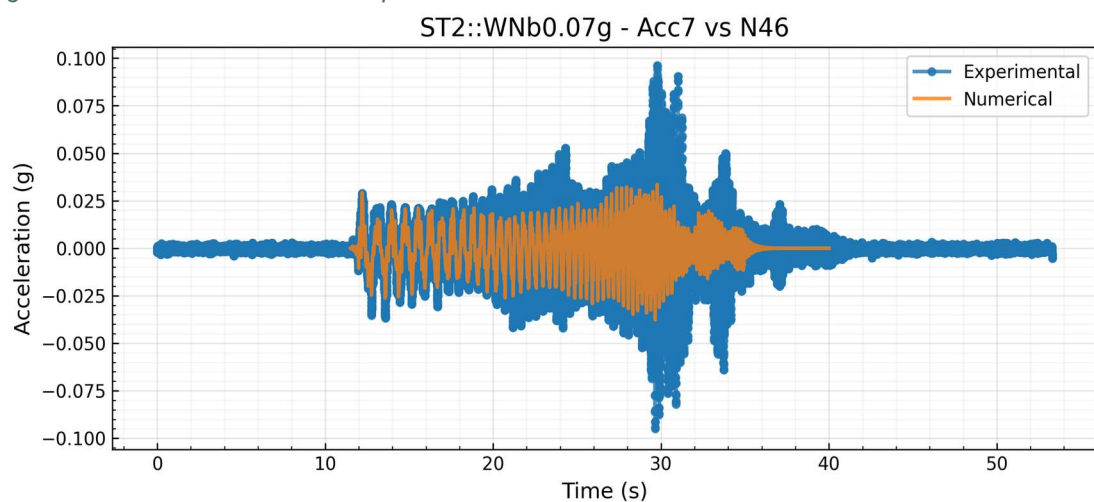


Figure 356 ST2 - Acceleration comparison Acc7 vs N46

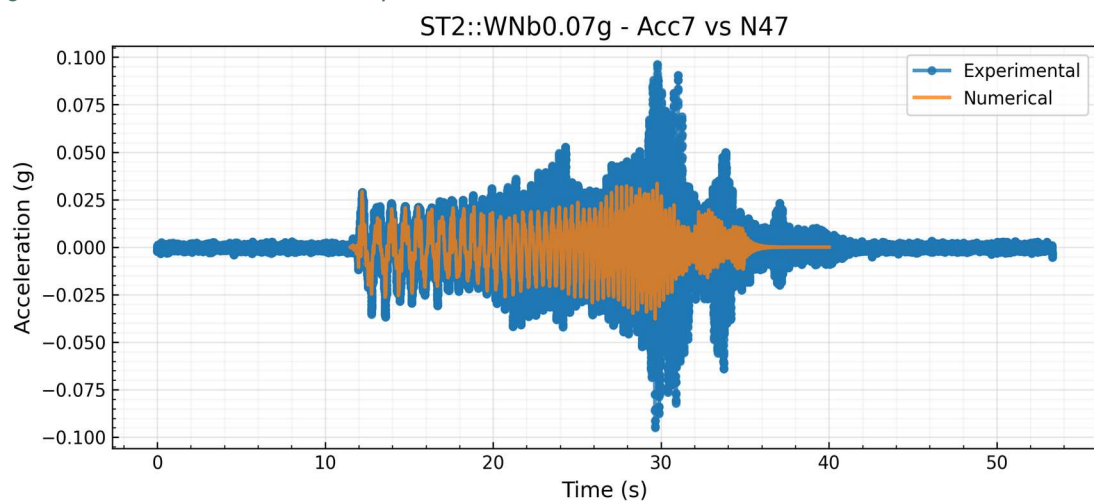


Figure 357 ST2 - Acceleration comparison Acc7 vs N47

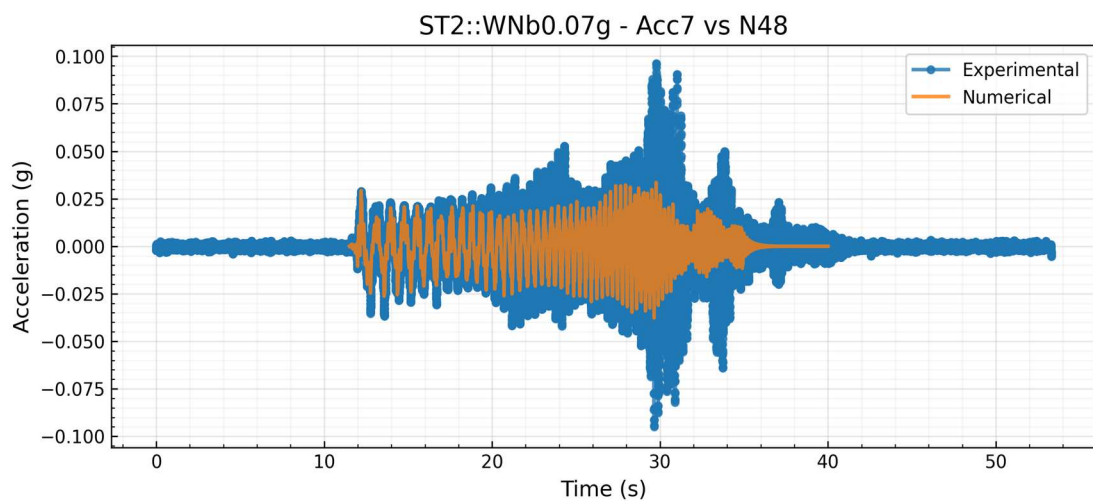


Figure 358 ST2 - Acceleration comparison Acc7 vs N48

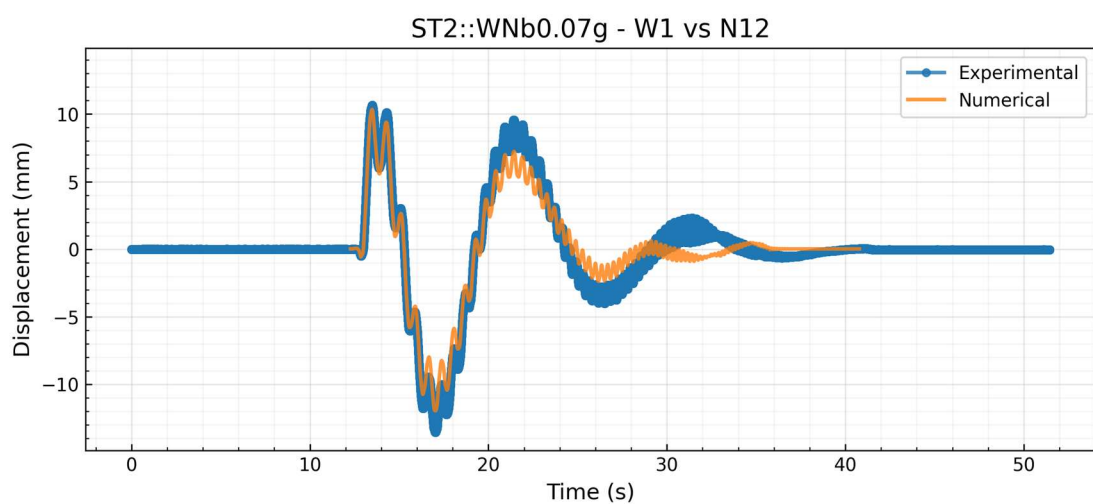


Figure 359 ST2 - Displacement comparison W1 vs N12

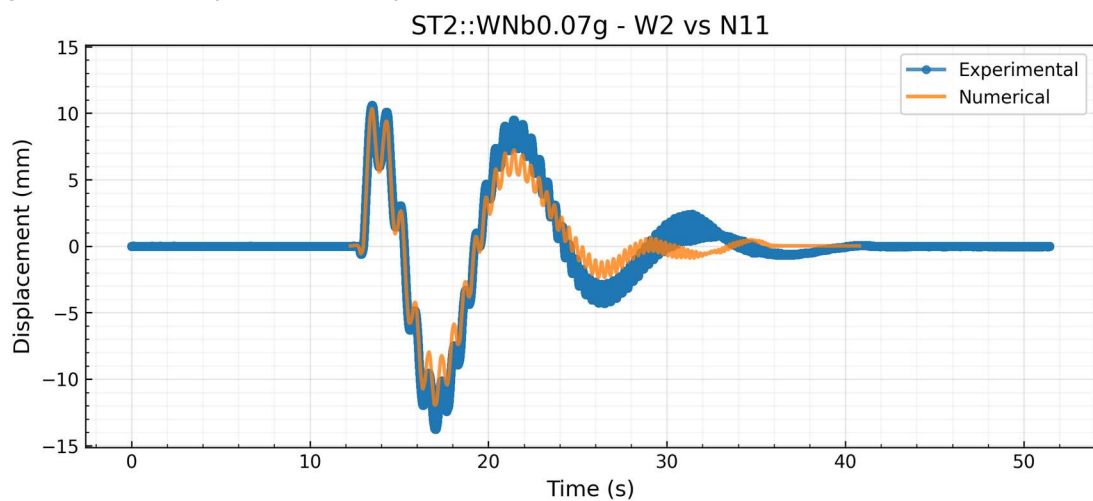


Figure 360 ST2 - Displacement comparison W2 vs N11

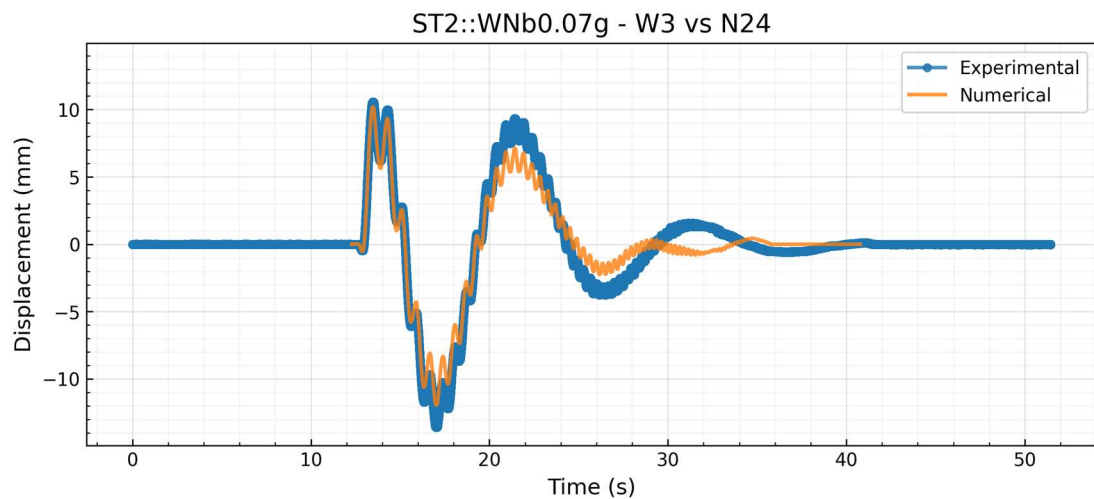


Figure 361 ST2 - Displacement comparison W3 vs N24

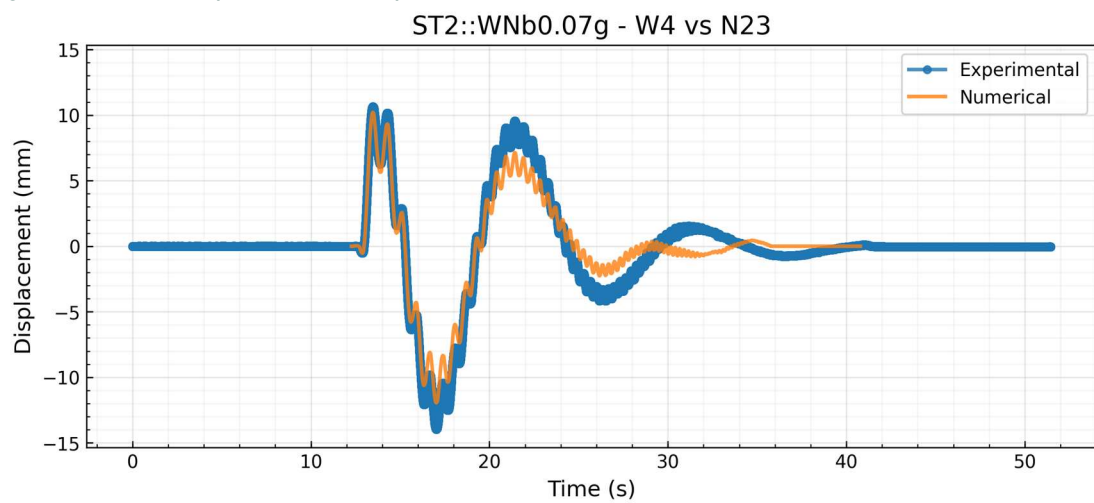


Figure 362 ST2 - Displacement comparison W4 vs N23

6.18 ST5::WNB0.14G RESULTS

The result for draw-wires and accelerometers for ST5::WNB0.14g are presented here.

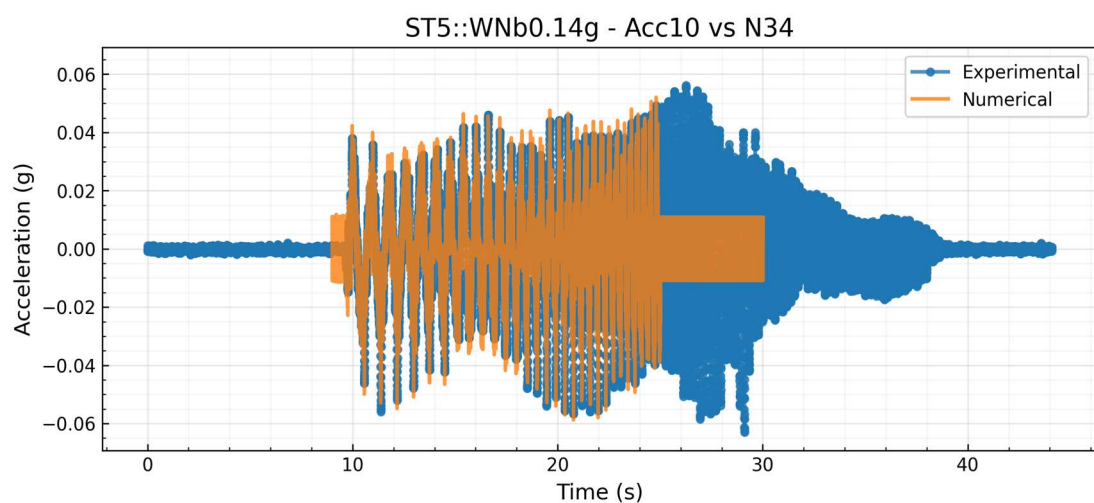


Figure 363 ST5 - Acceleration comparison Acc10 vs N34

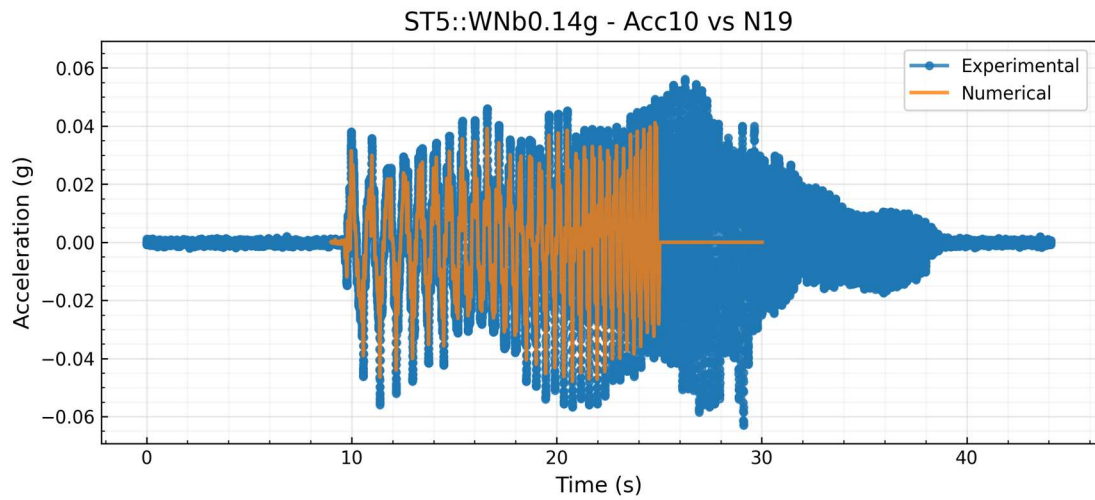


Figure 364 ST5 - Acceleration comparison Acc10 vs N19

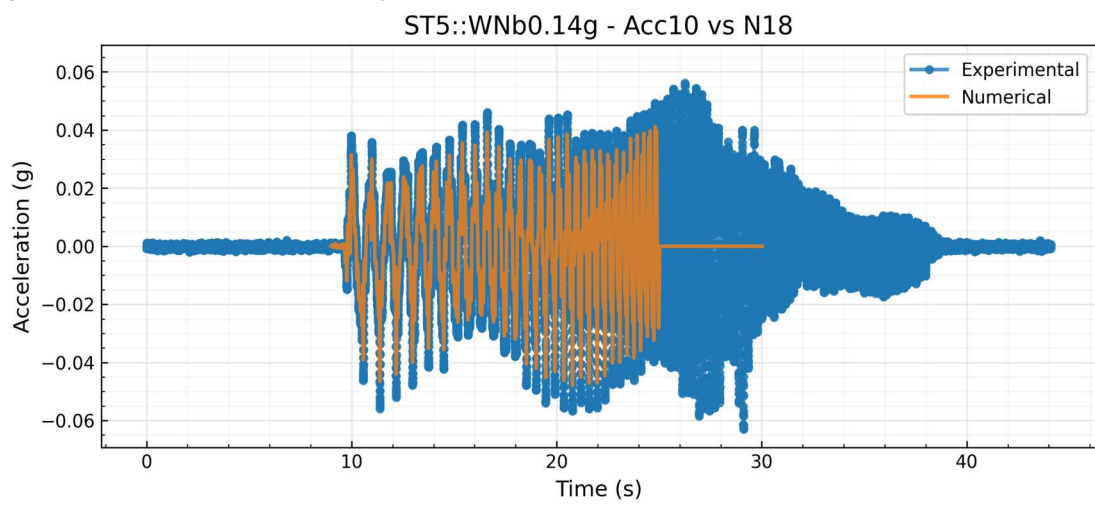


Figure 365 ST5 - Acceleration comparison Acc10 vs N18

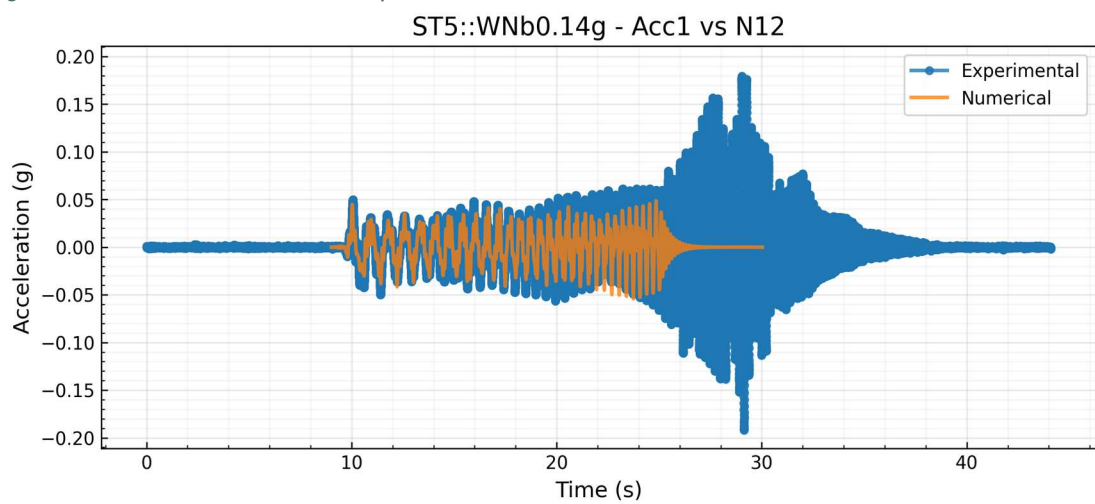


Figure 366 ST5 - Acceleration comparison Acc1 vs N12

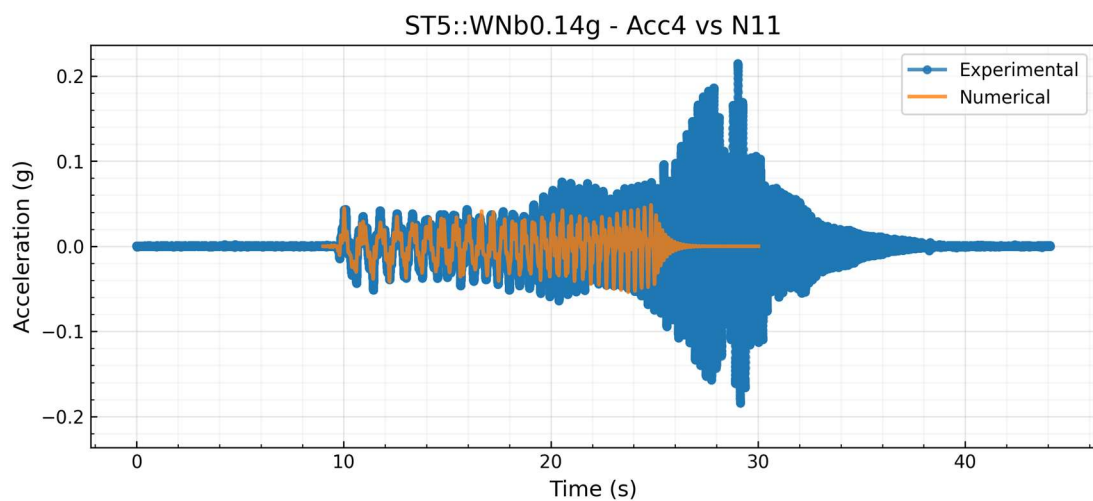


Figure 367 ST5 - Acceleration comparison Acc4 vs N11

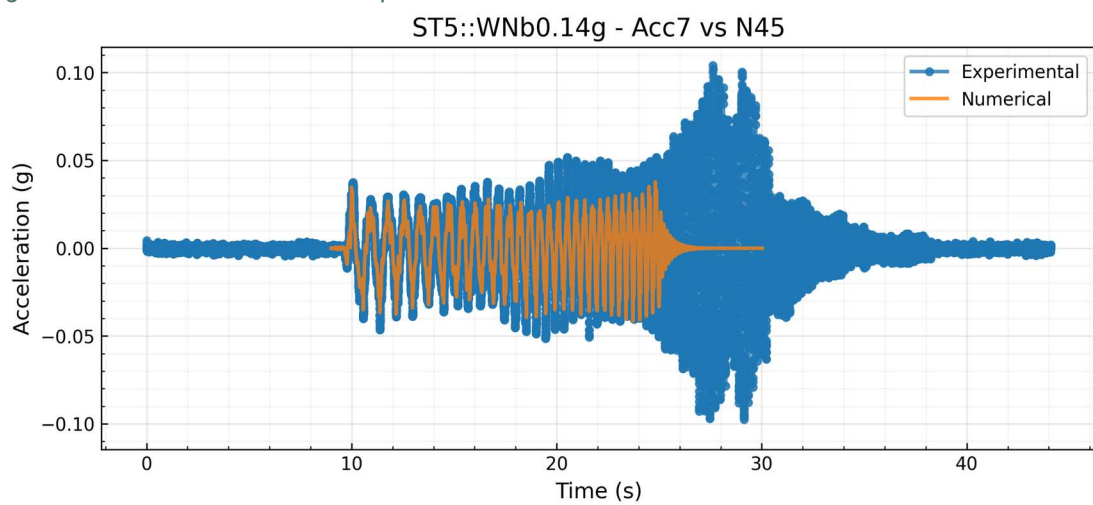


Figure 368 ST5 - Acceleration comparison Acc7 vs N45

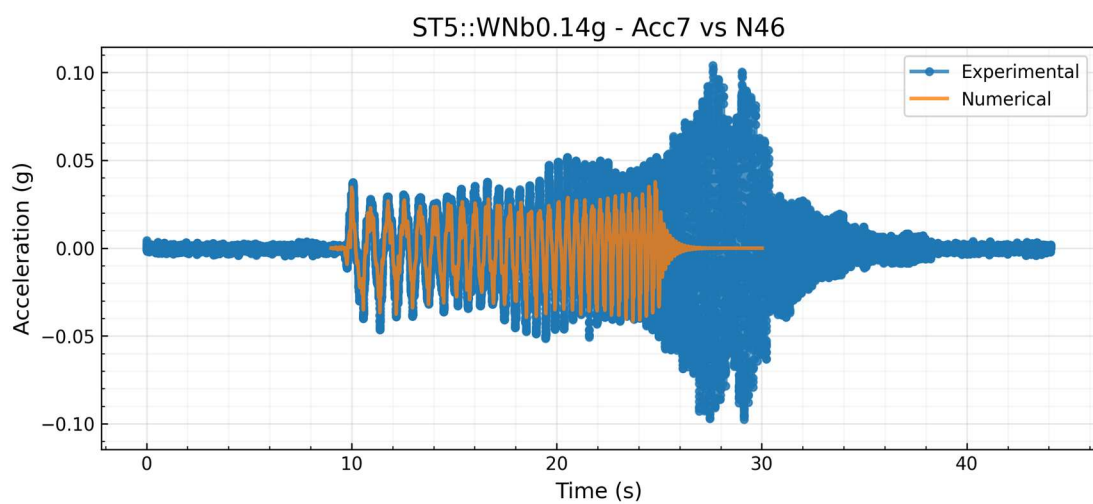


Figure 369 ST5 - Acceleration comparison Acc7 vs N46

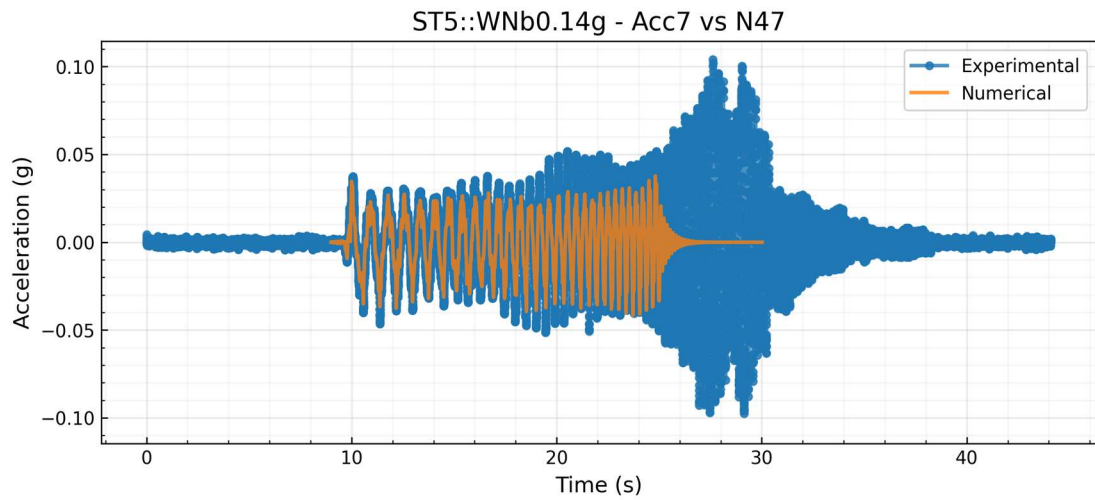


Figure 370 ST5 - Acceleration comparison Acc7 vs N47

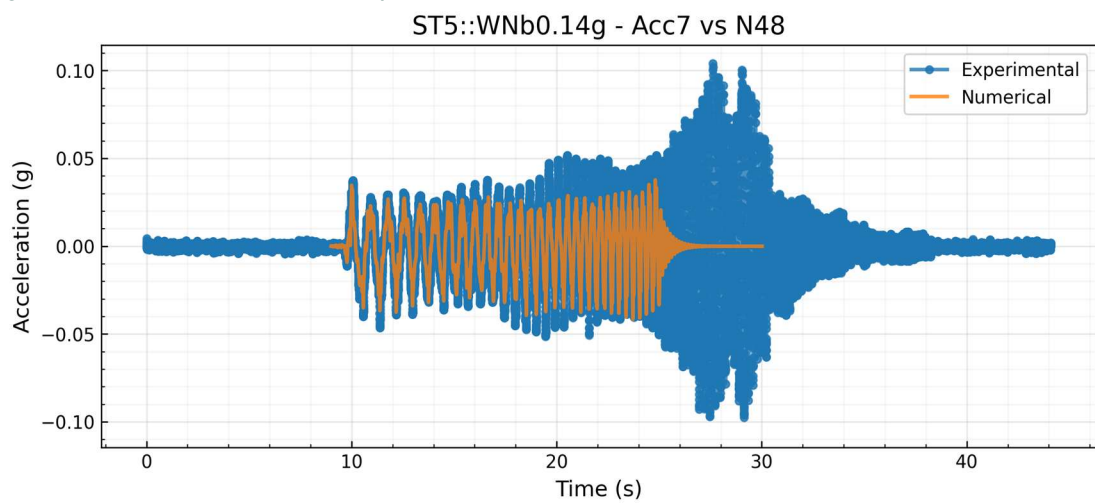


Figure 371 ST5 - Acceleration comparison Acc7 vs N48

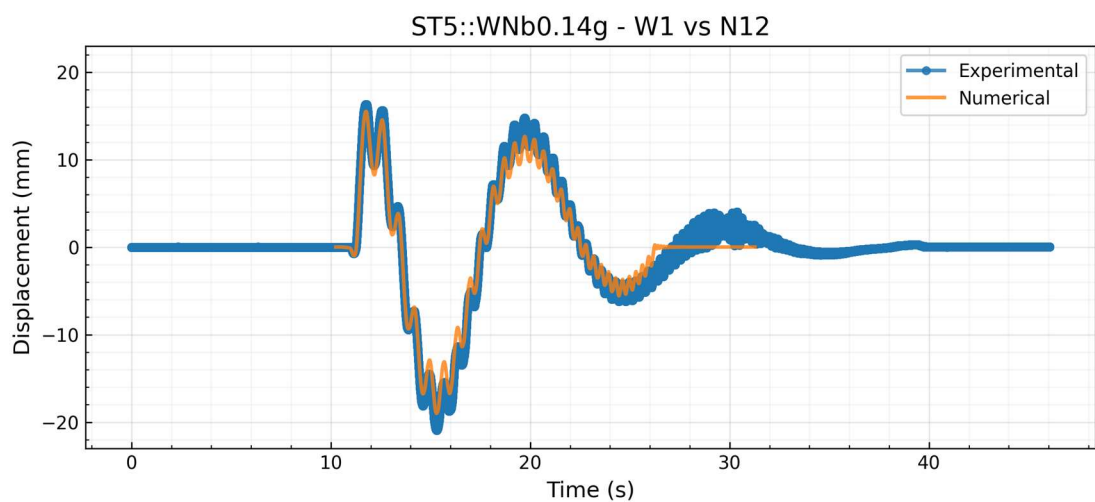


Figure 372 ST5 - Displacement comparison W1 vs N12

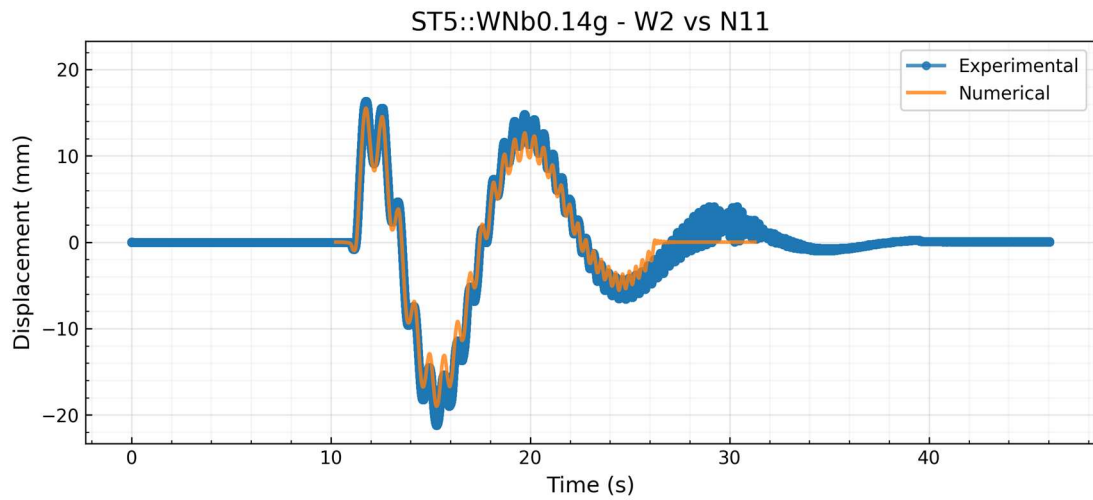


Figure 373 ST5 - Displacement comparison W2 vs N11

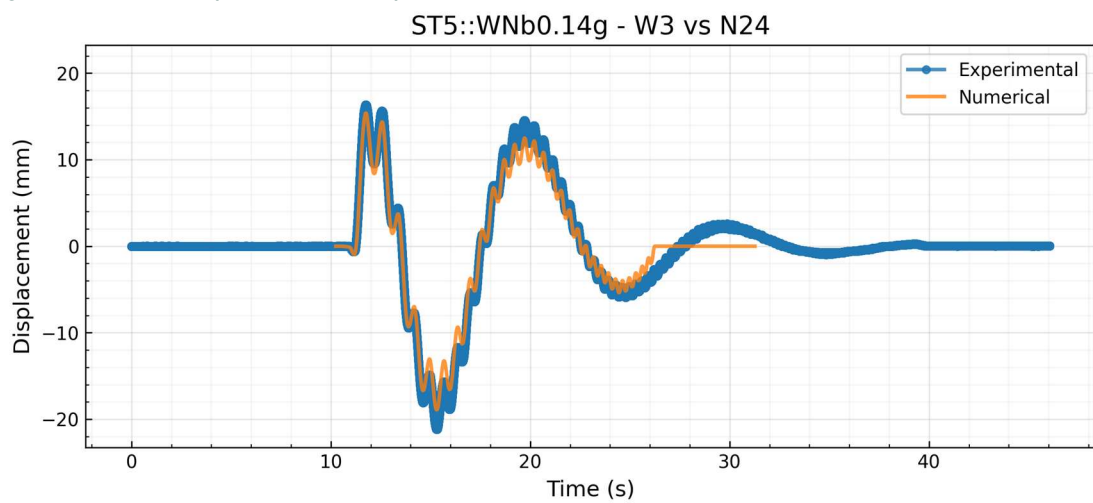


Figure 374 ST5 - Displacement comparison W3 vs N24

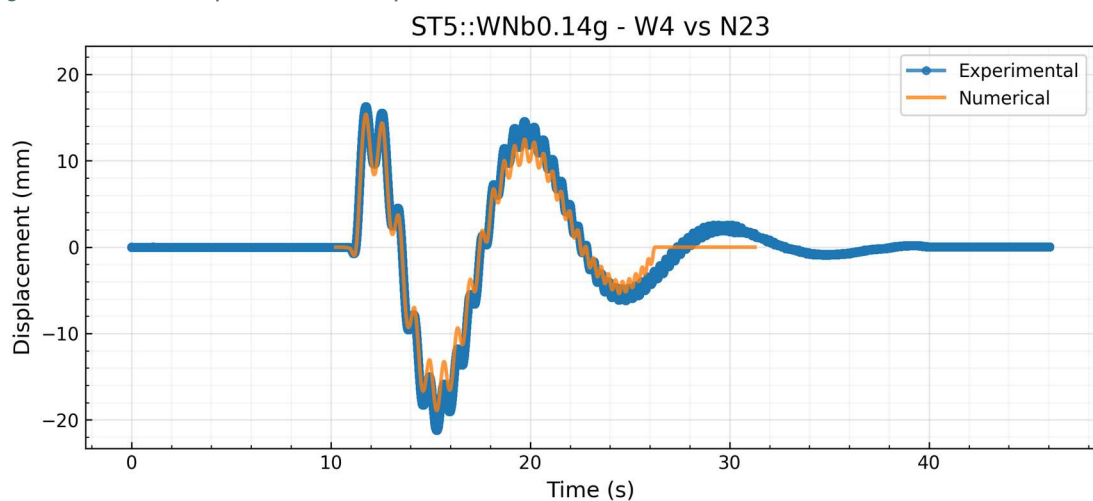


Figure 375 ST5 - Displacement comparison W4 vs N23

6.19 ST8::WNB0.34G RESULTS

The result for draw-wires and accelerometers for ST8::WNB0.34g are presented here.

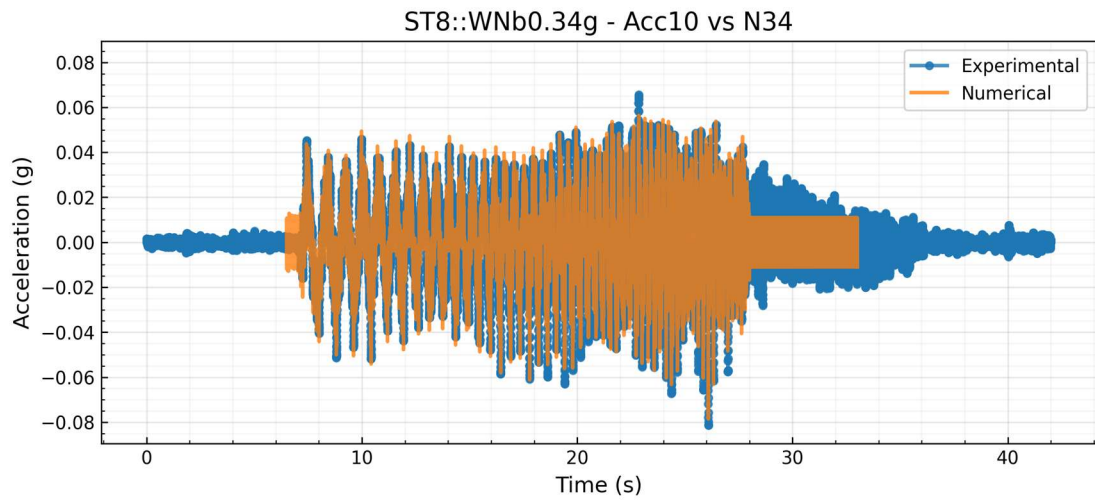


Figure 376 ST8 - Acceleration comparison Acc10 vs N34

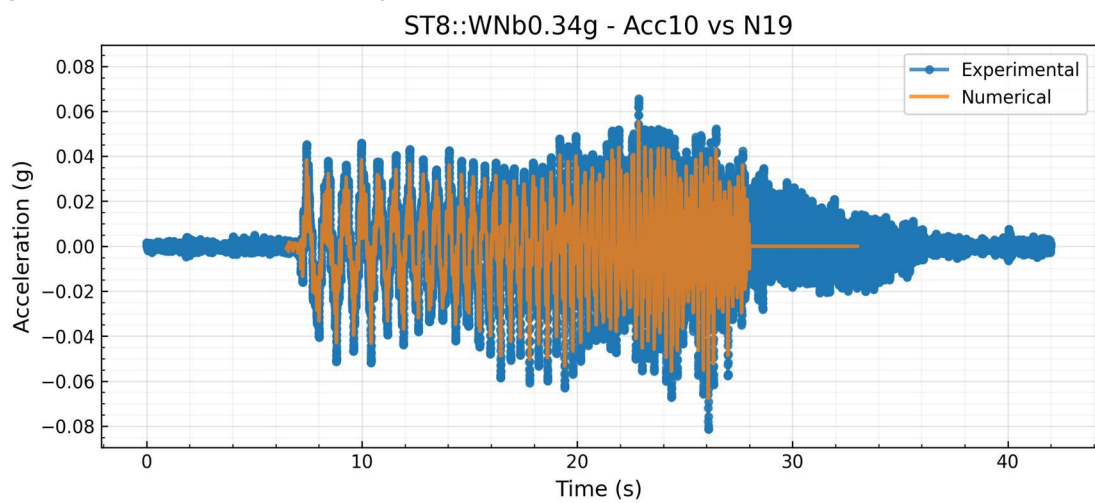


Figure 377 ST8 - Acceleration comparison Acc10 vs N19

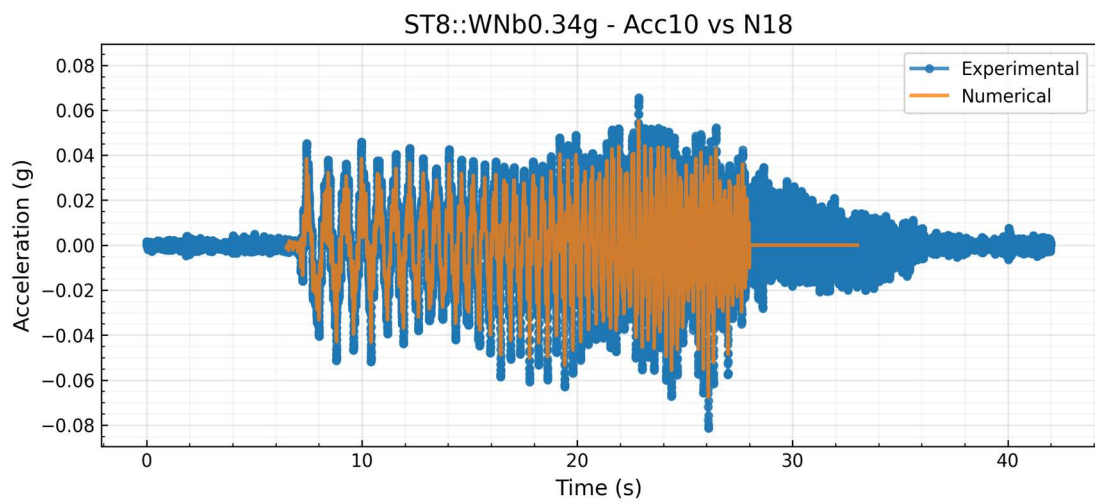


Figure 378 ST8 - Acceleration comparison Acc10 vs N18

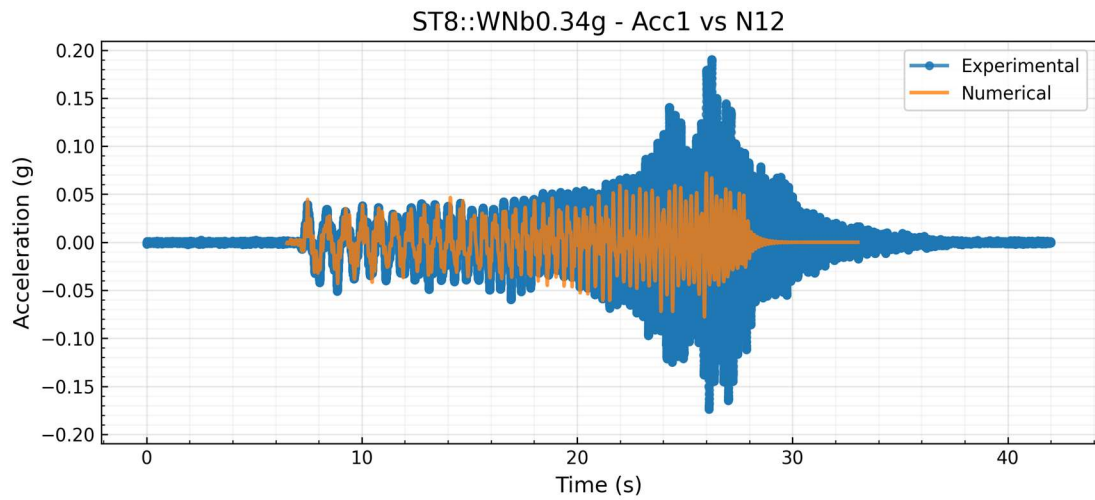


Figure 379 ST8 - Acceleration comparison Acc1 vs N12

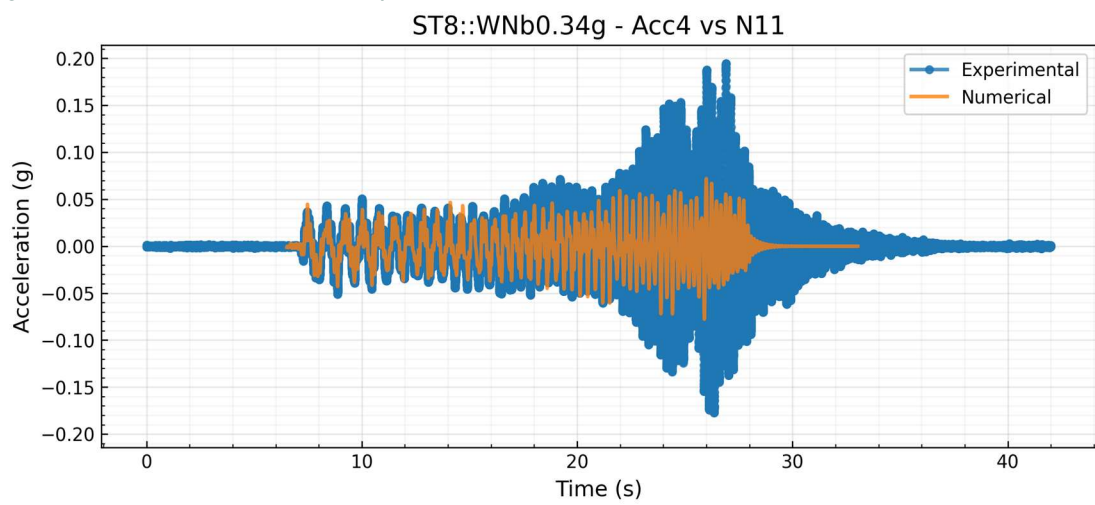


Figure 380 ST8 - Acceleration comparison Acc4 vs N11

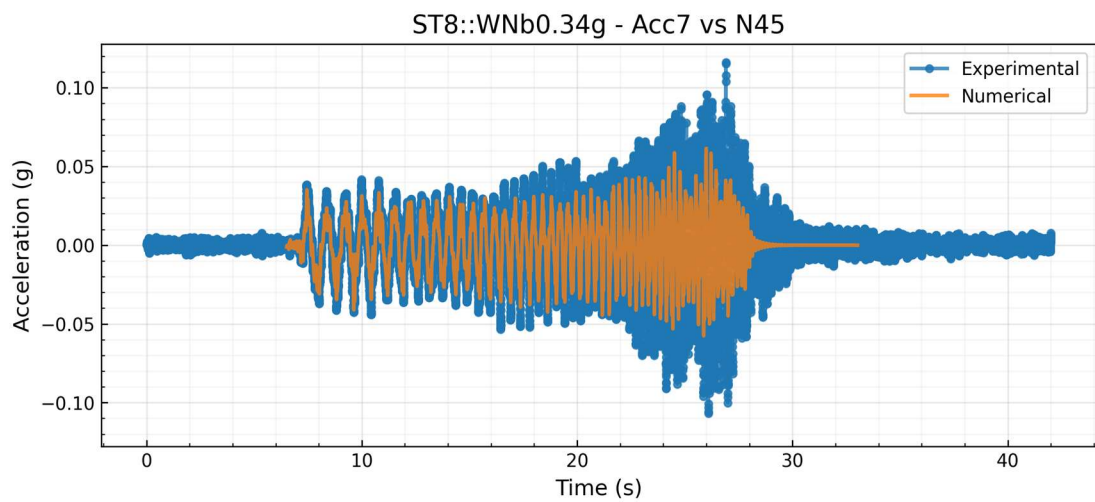


Figure 381 ST8 - Acceleration comparison Acc7 vs N45

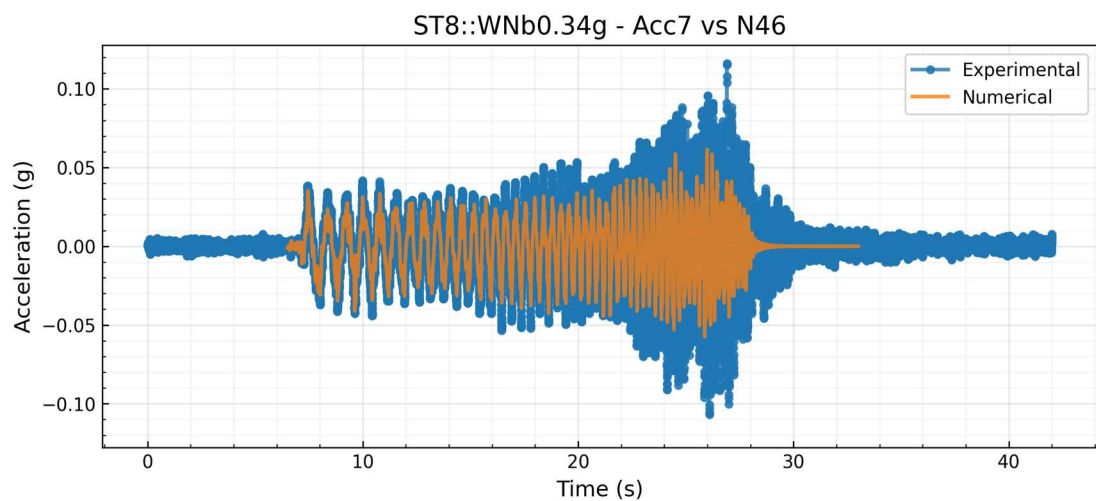


Figure 382 ST8 - Acceleration comparison Acc7 vs N46

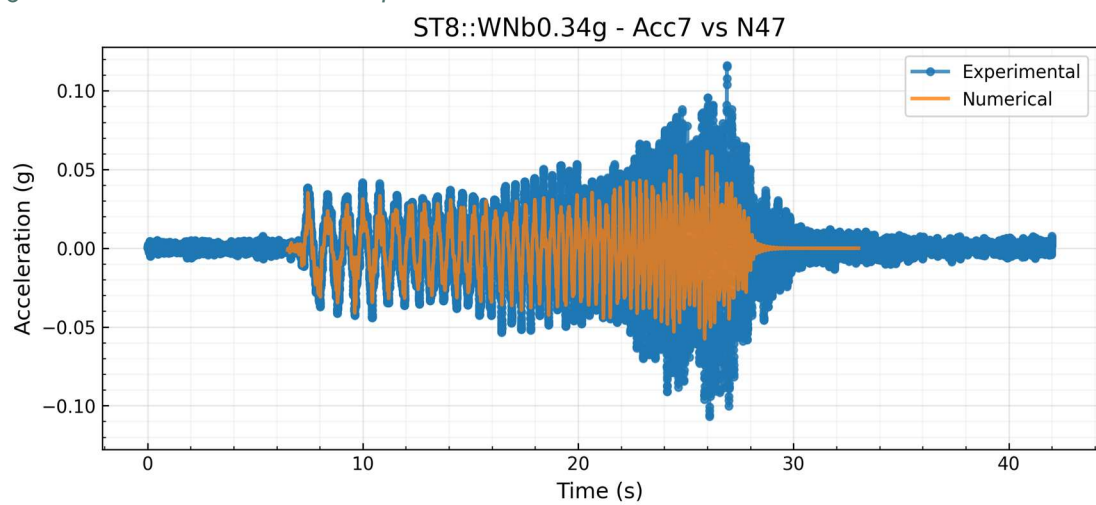


Figure 383 ST8 - Acceleration comparison Acc7 vs N47

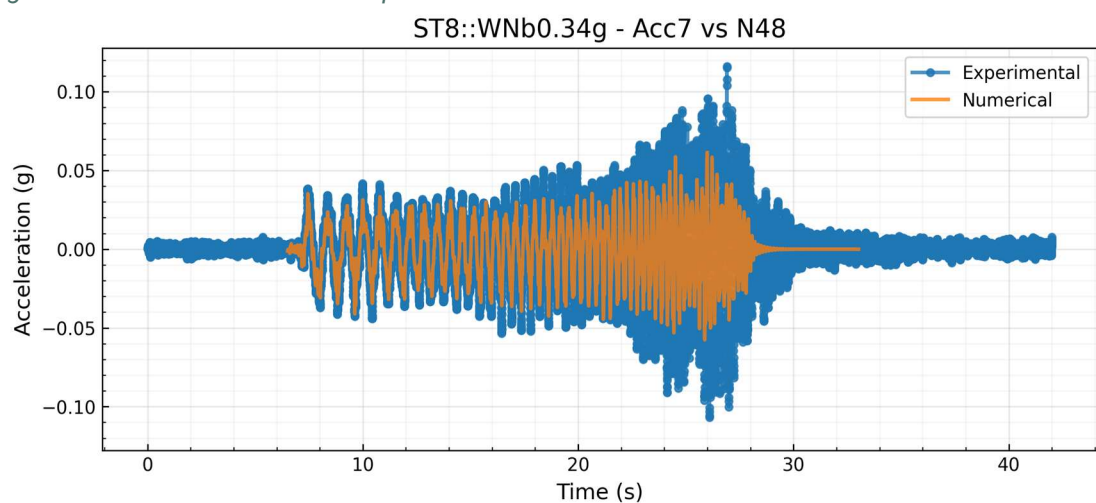


Figure 384 ST8 - Acceleration comparison Acc7 vs N48

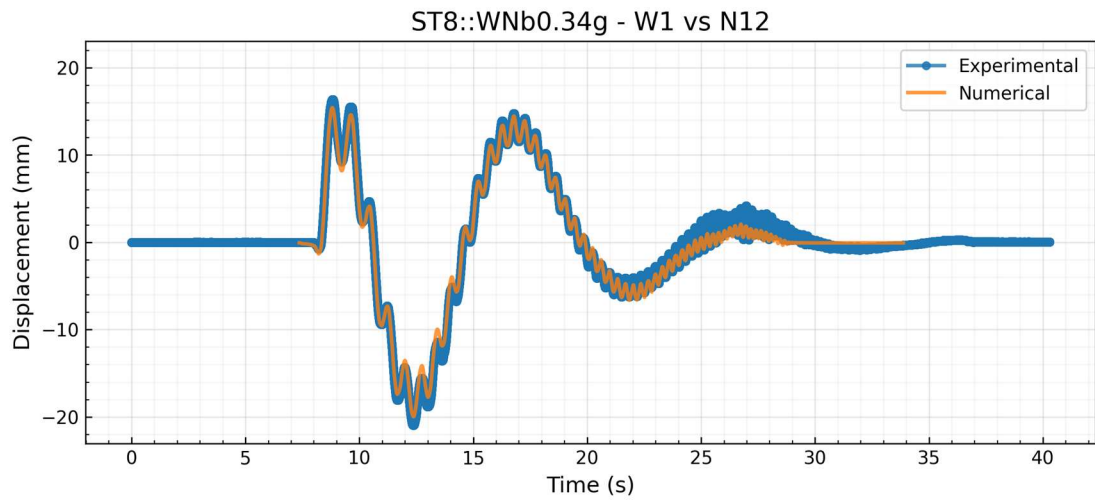


Figure 385 ST8 - Displacement comparison W1 vs N12

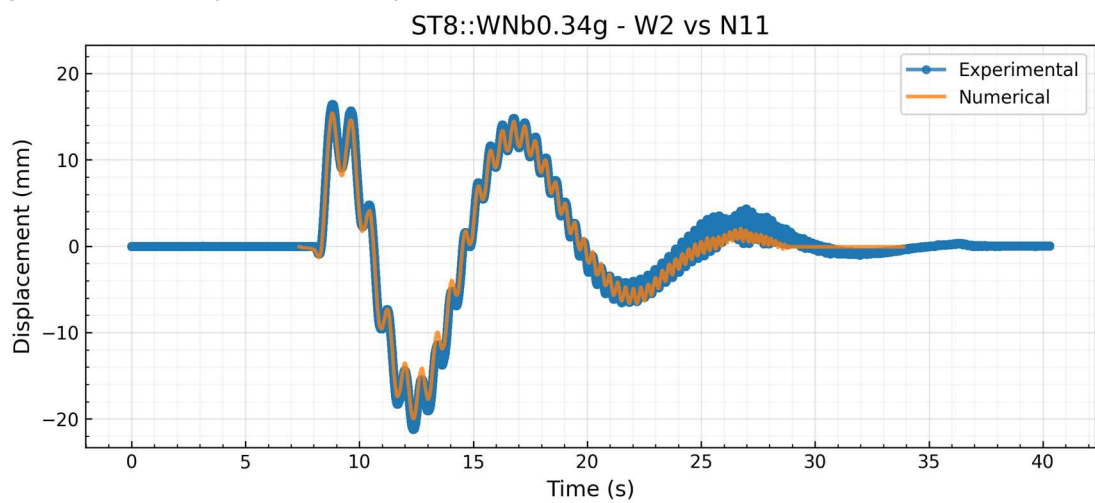


Figure 386 ST8 - Displacement comparison W2 vs N11

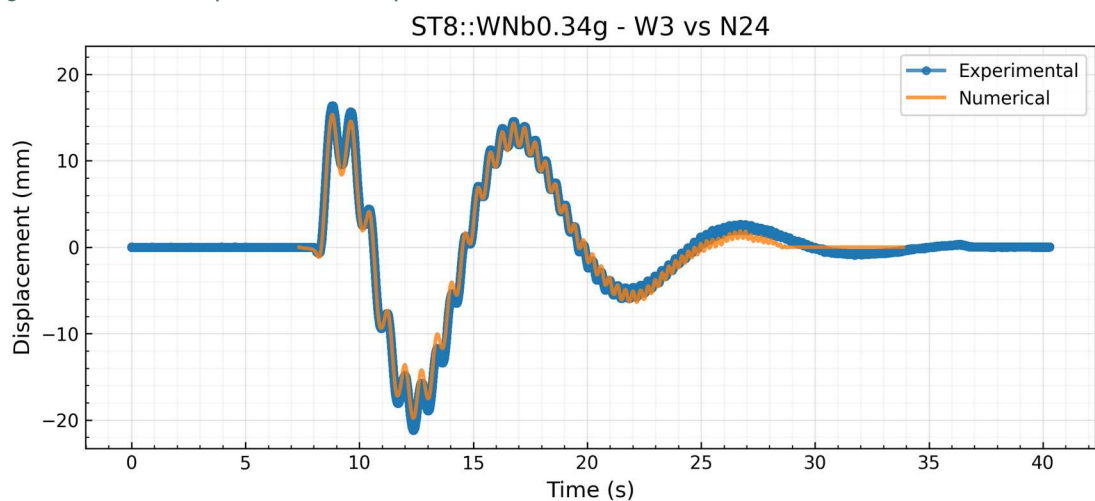


Figure 387 ST8 - Displacement comparison W3 vs N24

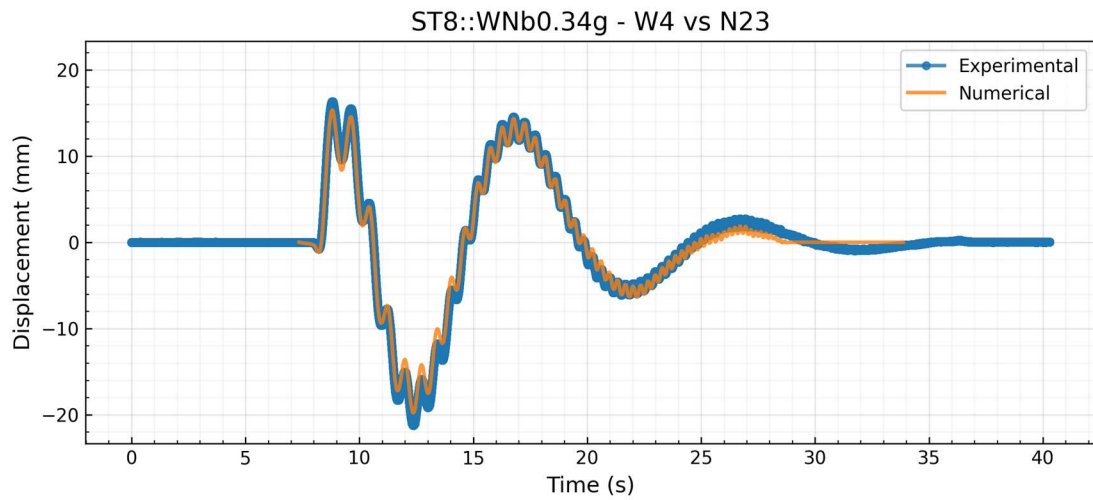


Figure 388 ST8 - Displacement comparison W4 vs N23

6.20 ST10::WNB0.5G RESULTS

The result for draw-wires and accelerometers for ST10::WNB0.5g are presented here.

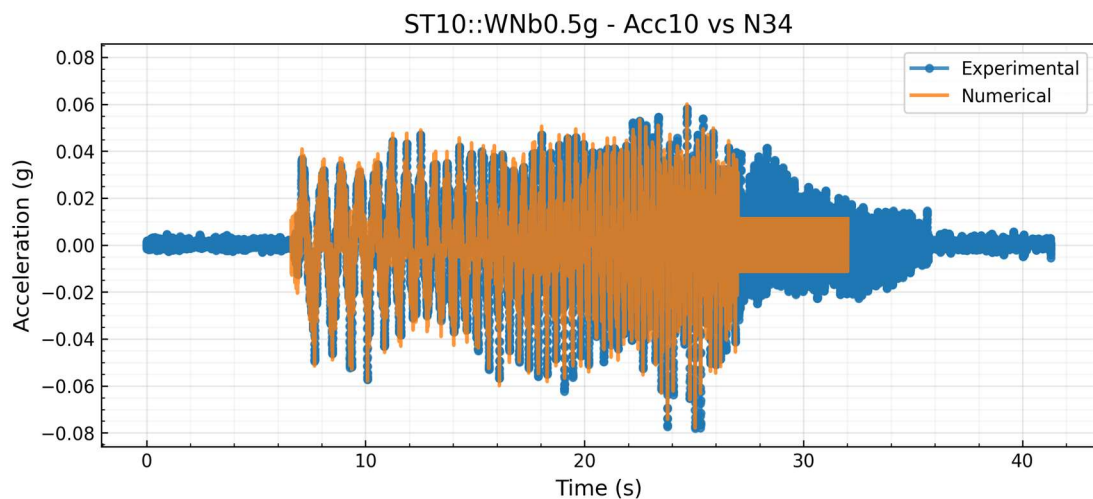


Figure 389 ST10 - Acceleration comparison Acc10 vs N34

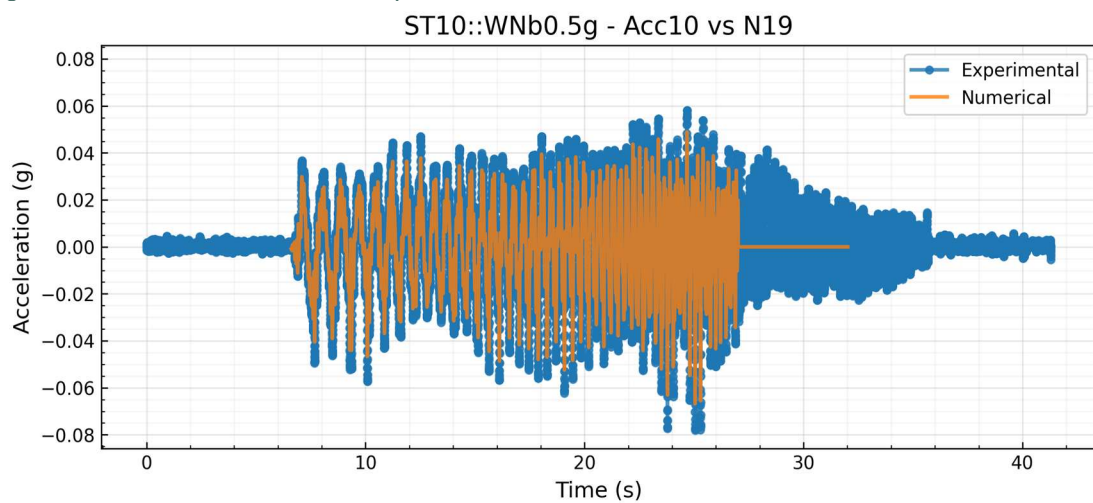


Figure 390 ST10 - Acceleration comparison Acc10 vs N19

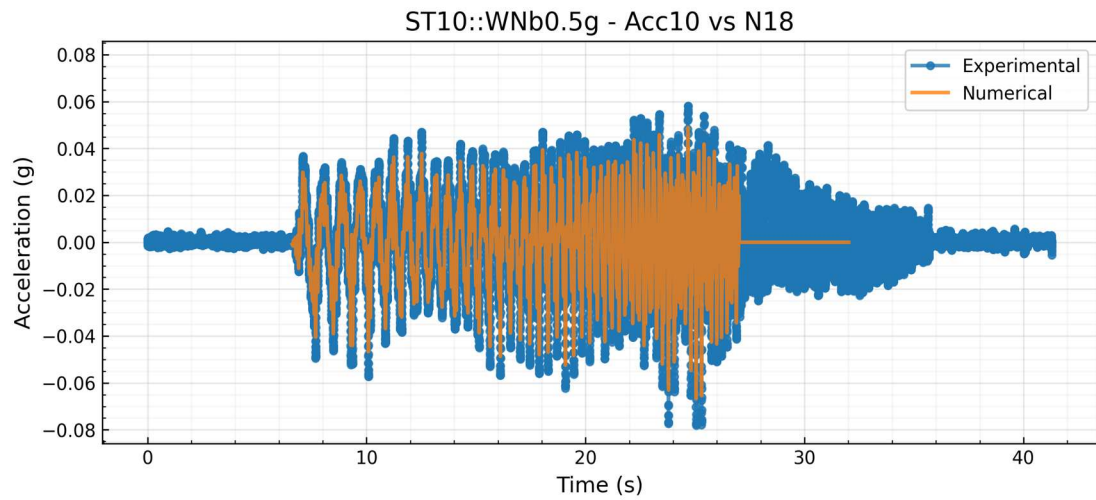


Figure 391 ST10 - Acceleration comparison Acc10 vs N18

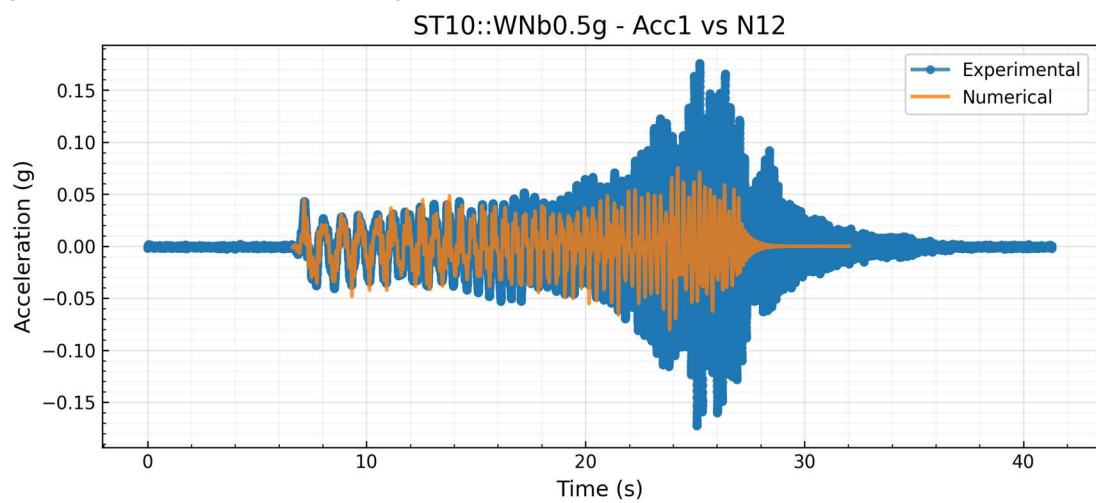


Figure 392 ST10 - Acceleration comparison Acc1 vs N12

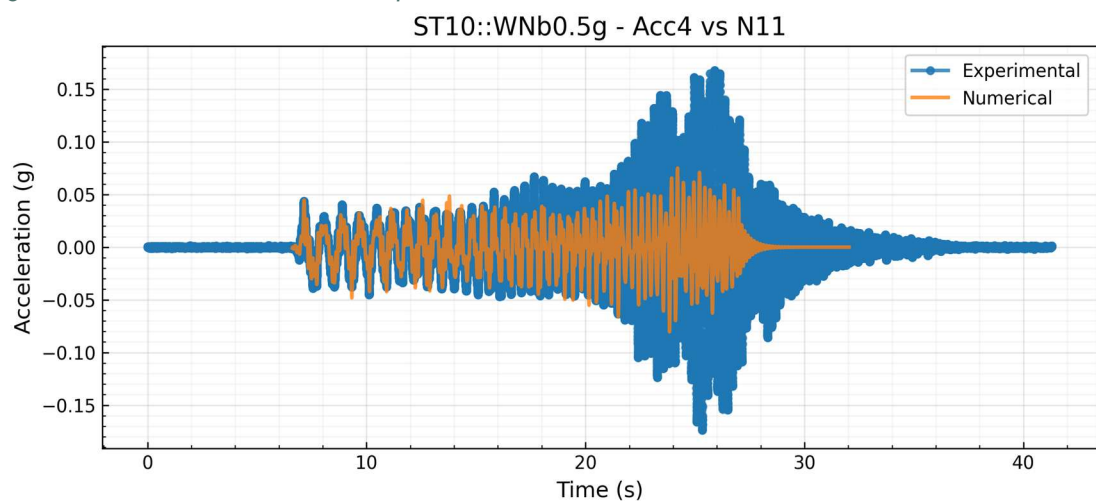


Figure 393 ST10 - Acceleration comparison Acc4 vs N11

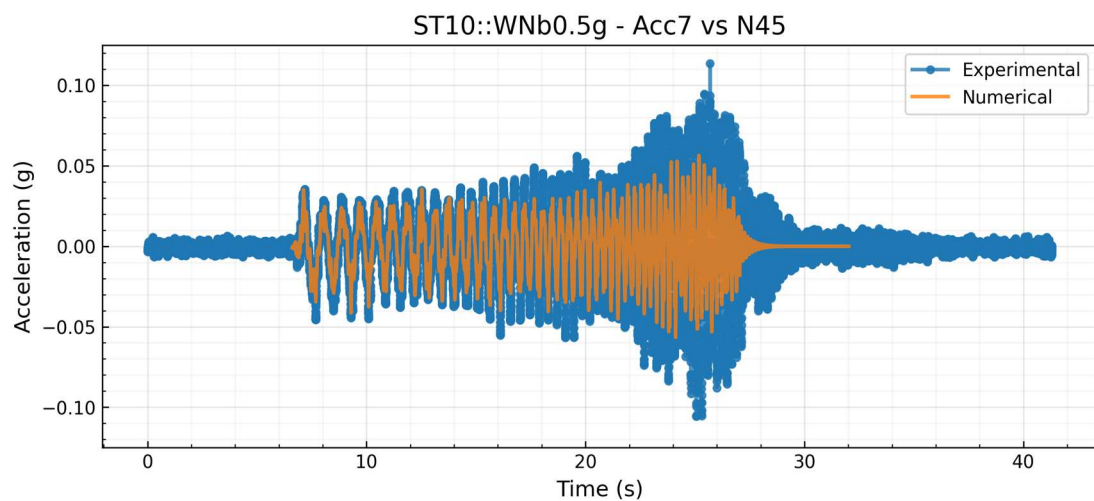


Figure 394 ST10 - Acceleration comparison Acc7 vs N45

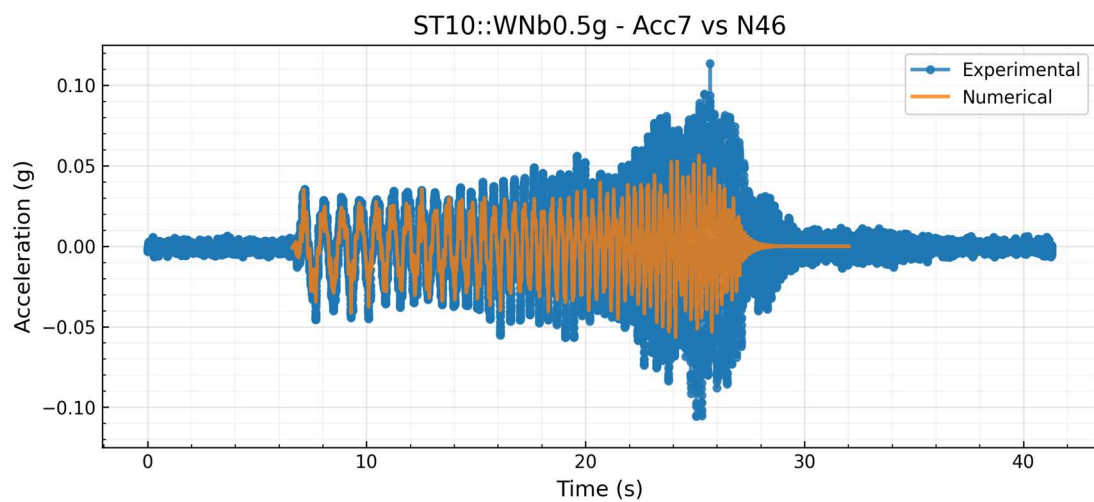


Figure 395 ST10 - Acceleration comparison Acc7 vs N46

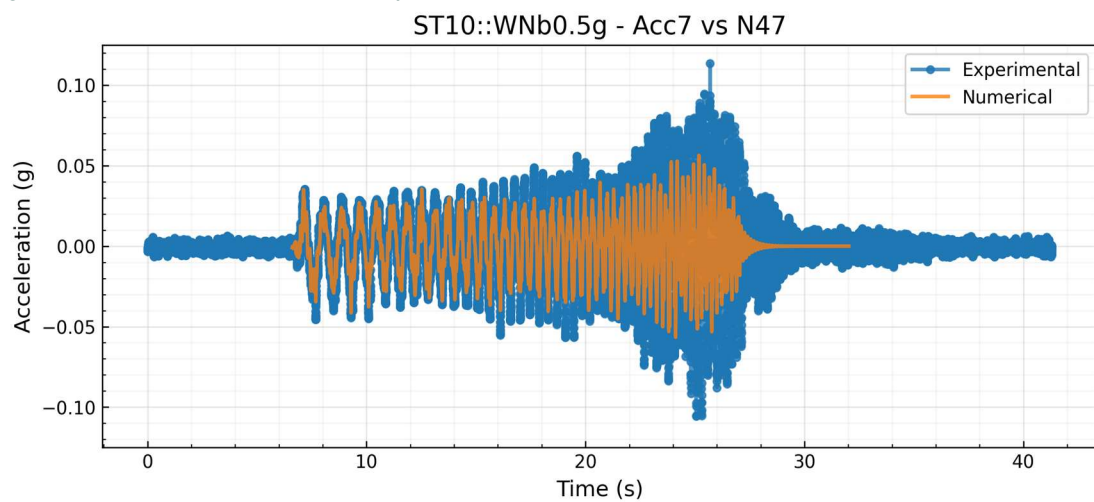


Figure 396 ST10 - Acceleration comparison Acc7 vs N47

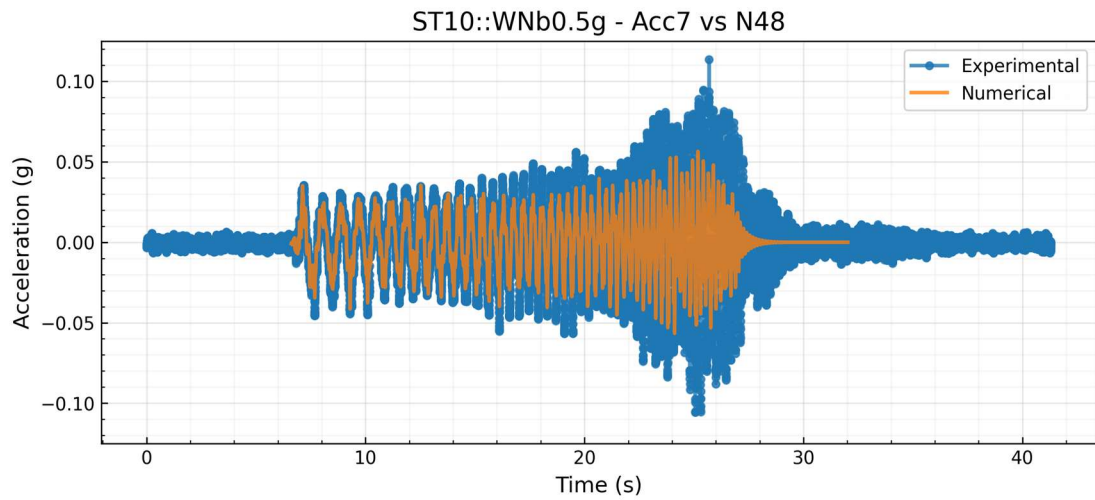


Figure 397 ST10 - Acceleration comparison Acc7 vs N48

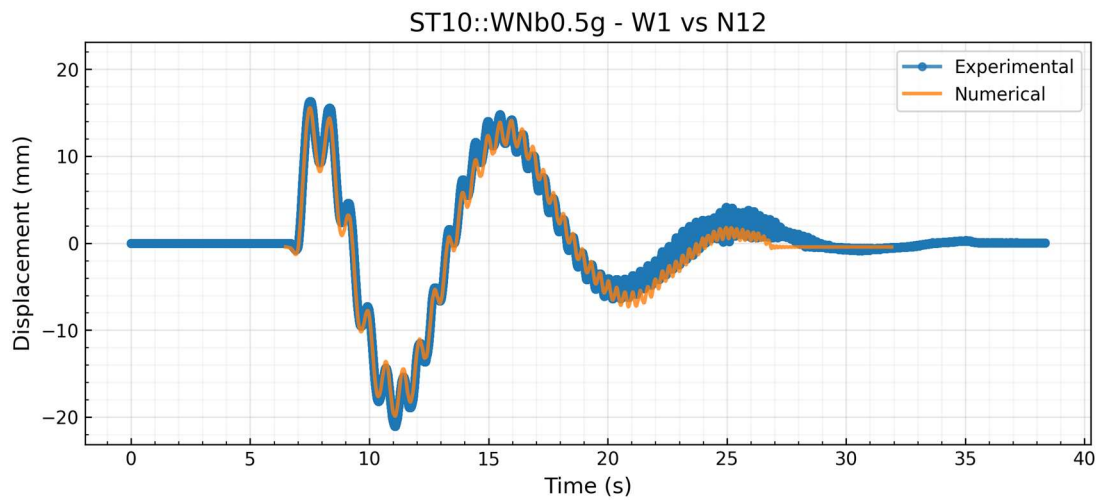


Figure 398 ST10 - Displacement comparison W1 vs N12

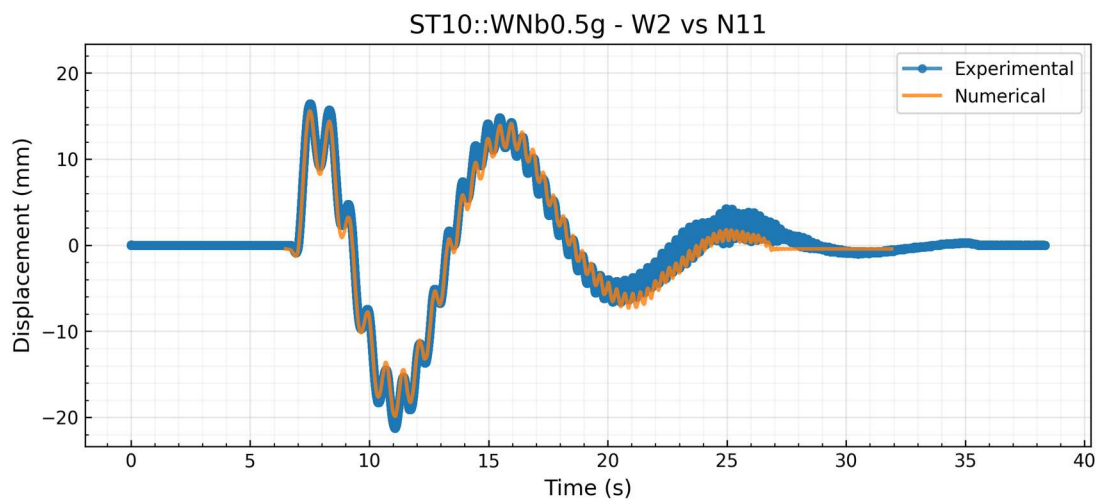


Figure 399 ST10 - Displacement comparison W2 vs N11

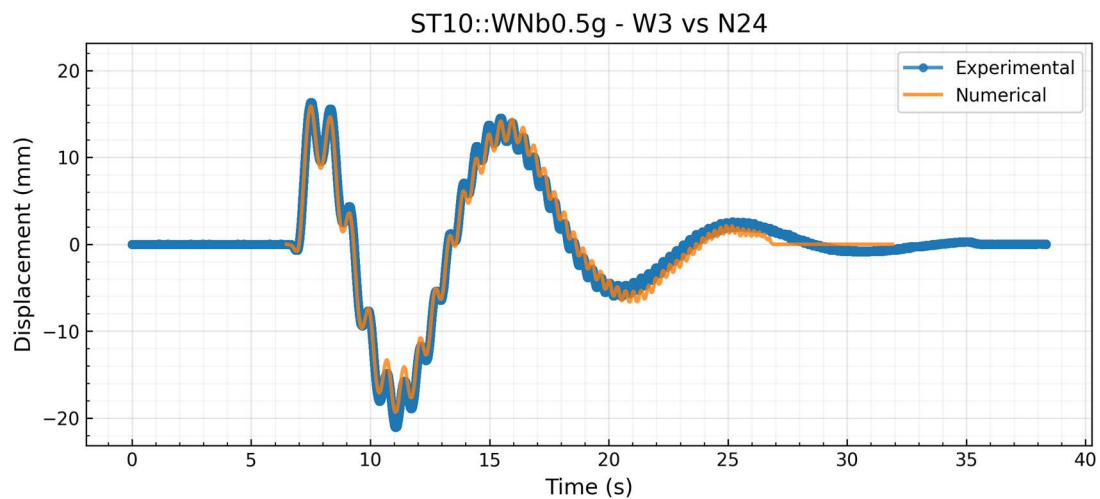


Figure 400 ST10 - Displacement comparison W3 vs N24

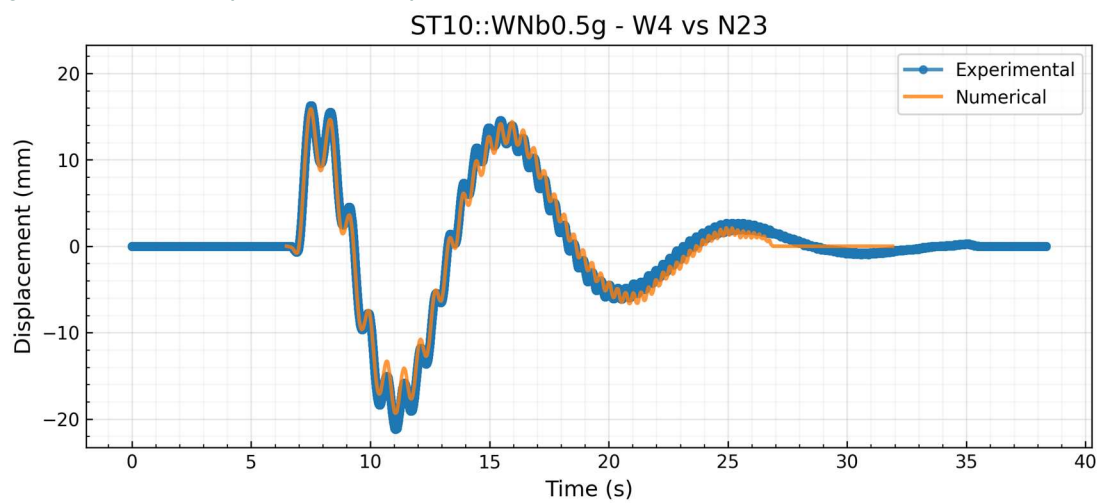


Figure 401 ST10 - Displacement comparison W4 vs N23

6.21 ST12::WNB0.55G RESULTS

The result for draw-wires and accelerometers for ST12::WNB0.55g are presented here.

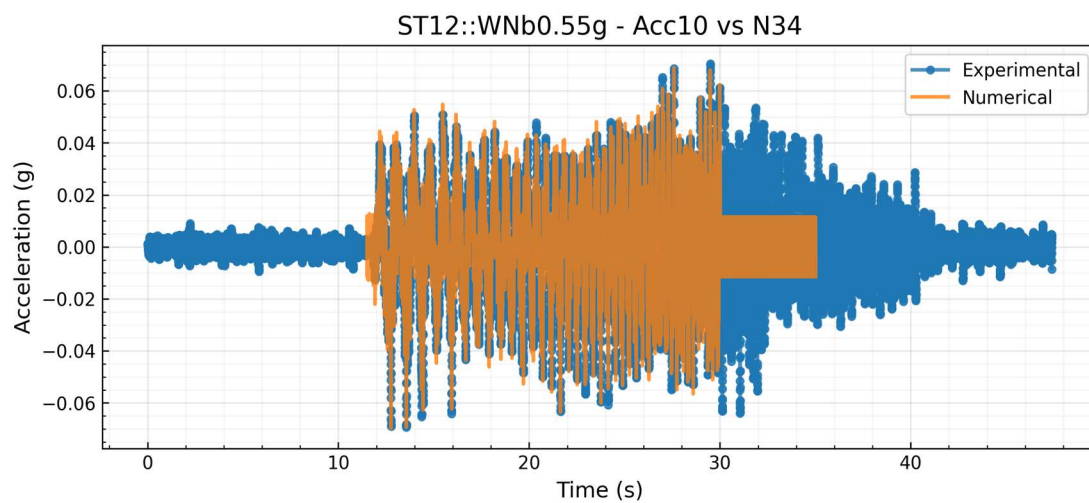


Figure 402 ST12 - Acceleration comparison Acc10 vs N34

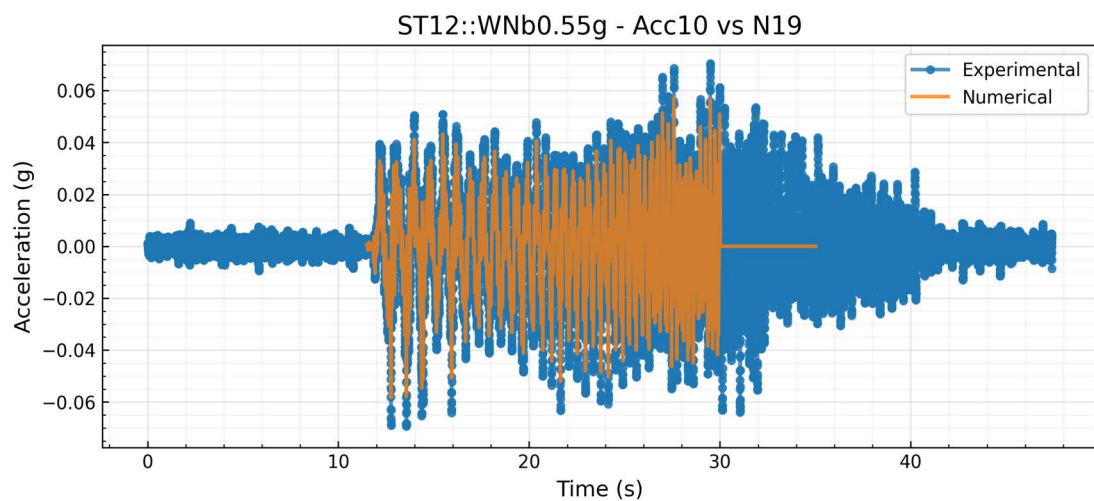


Figure 403 ST12 - Acceleration comparison Acc10 vs N19

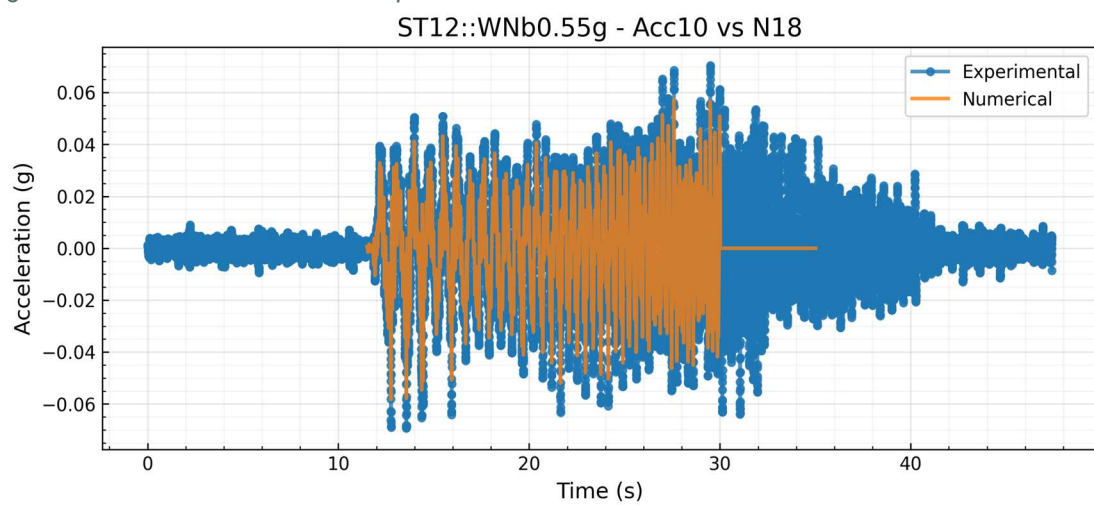


Figure 404 ST12 - Acceleration comparison Acc10 vs N18

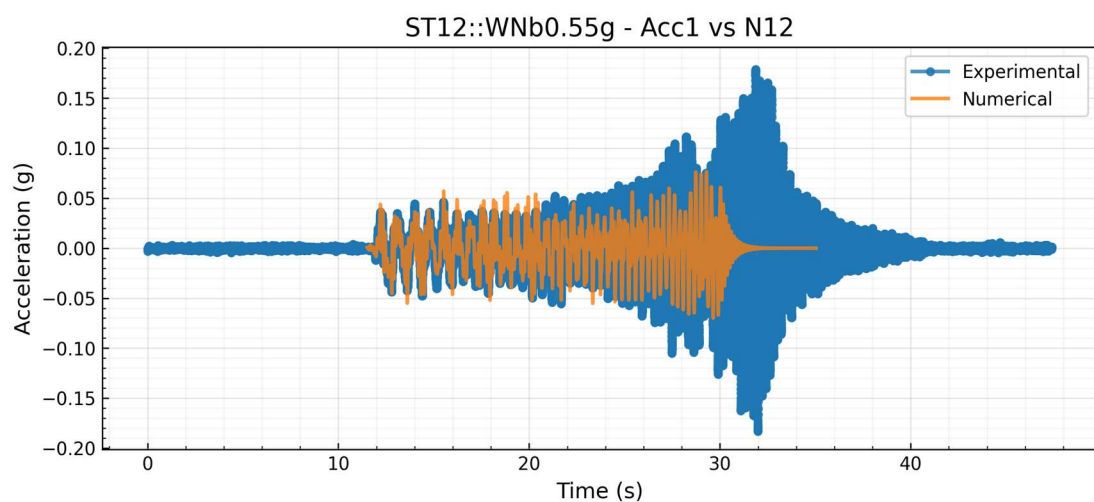


Figure 405 ST12 - Acceleration comparison Acc1 vs N12

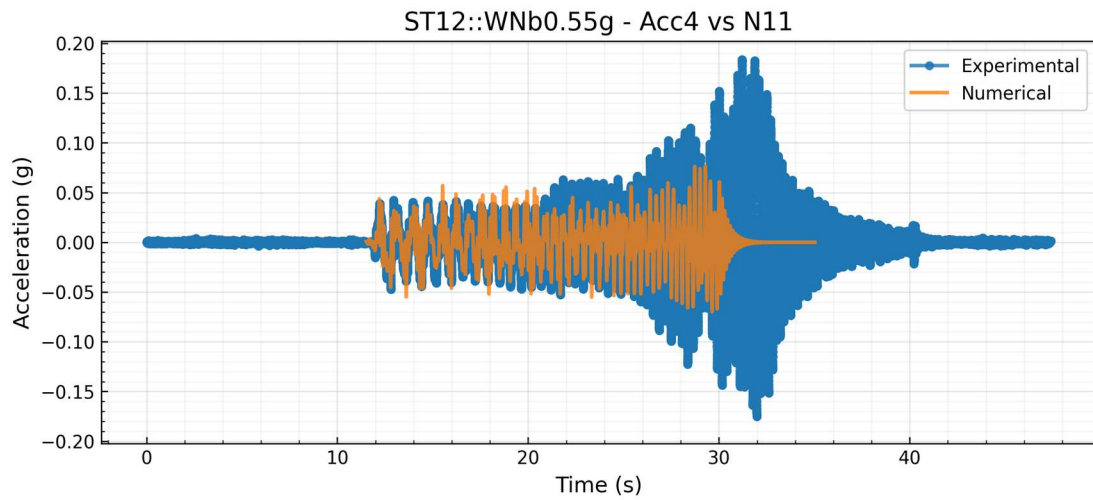


Figure 406 ST12 - Acceleration comparison Acc4 vs N11

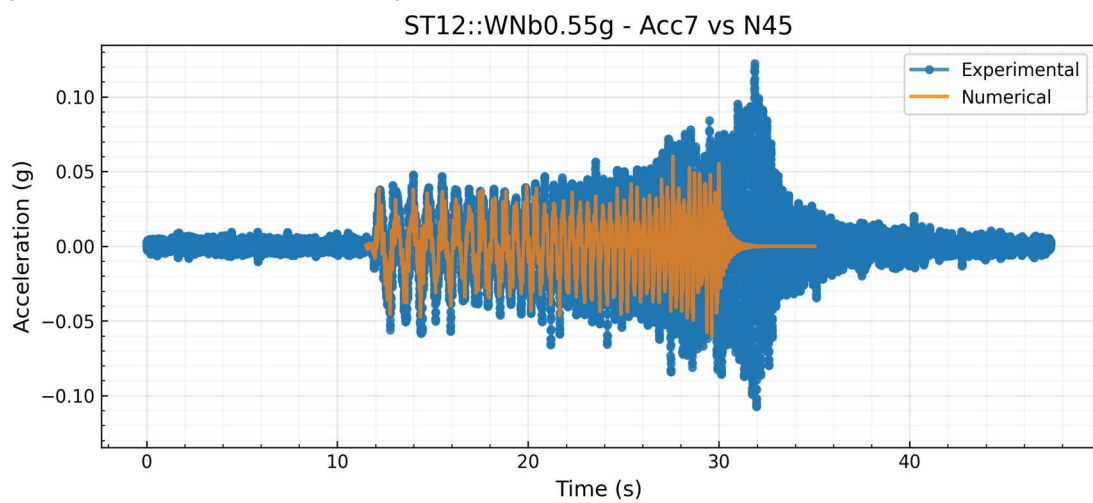


Figure 407 ST12 - Acceleration comparison Acc7 vs N45

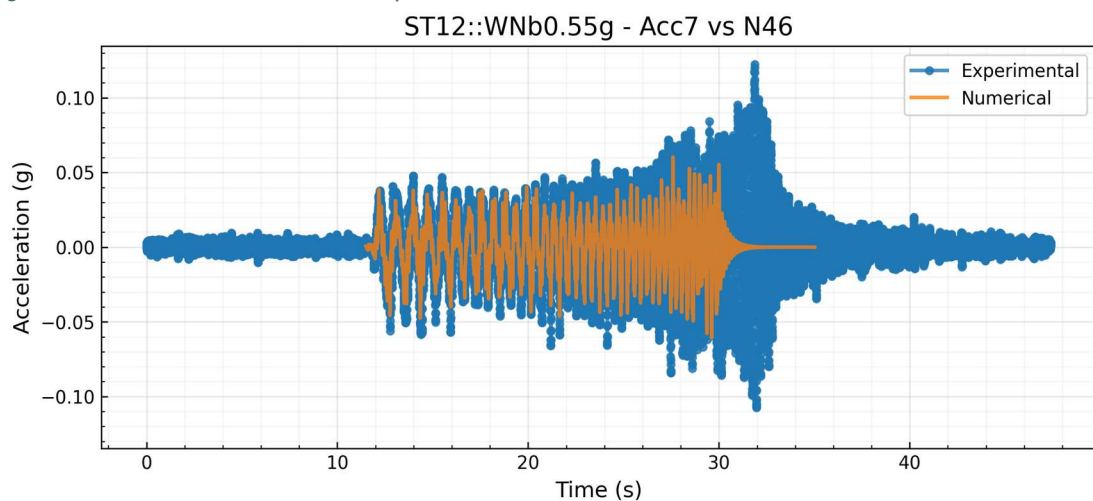


Figure 408 ST12 - Acceleration comparison Acc7 vs N46

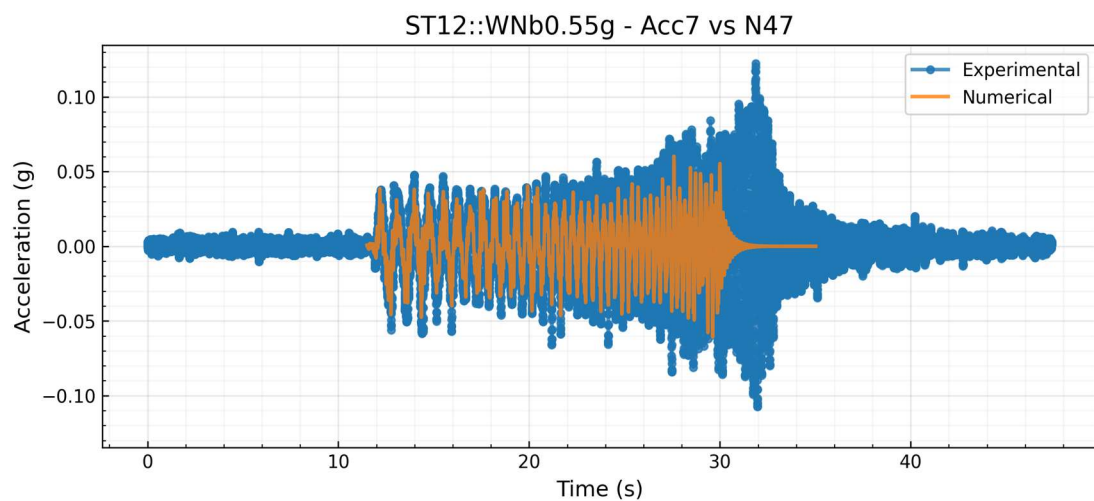


Figure 409 ST12 - Acceleration comparison Acc7 vs N47

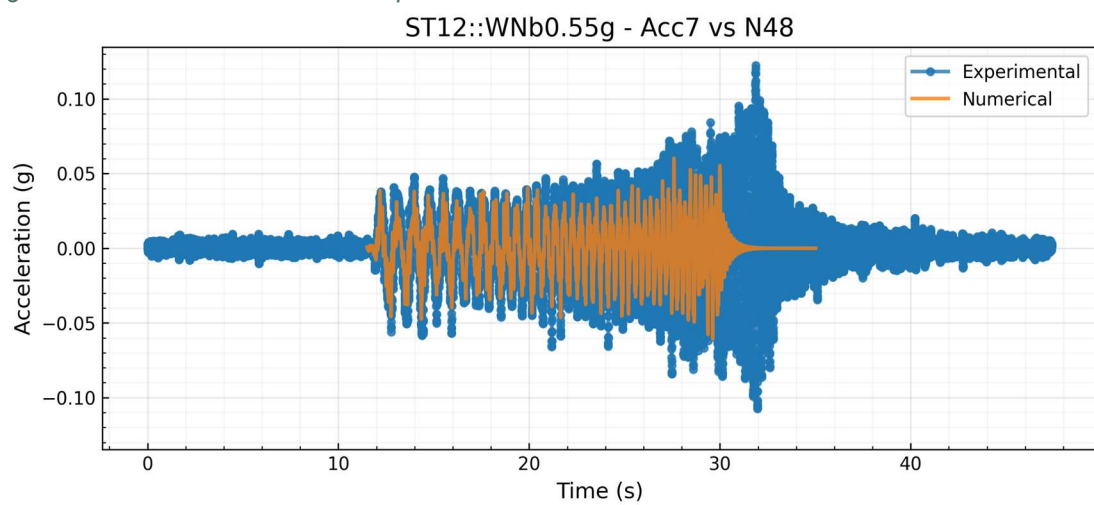


Figure 410 ST12 - Acceleration comparison Acc7 vs N48

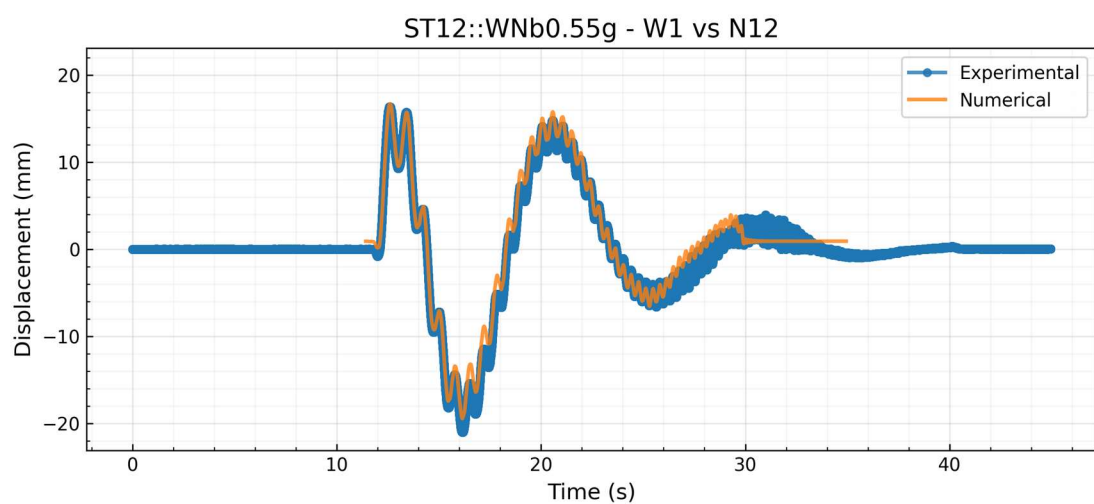


Figure 411 ST12 - Displacement comparison W1 vs N12

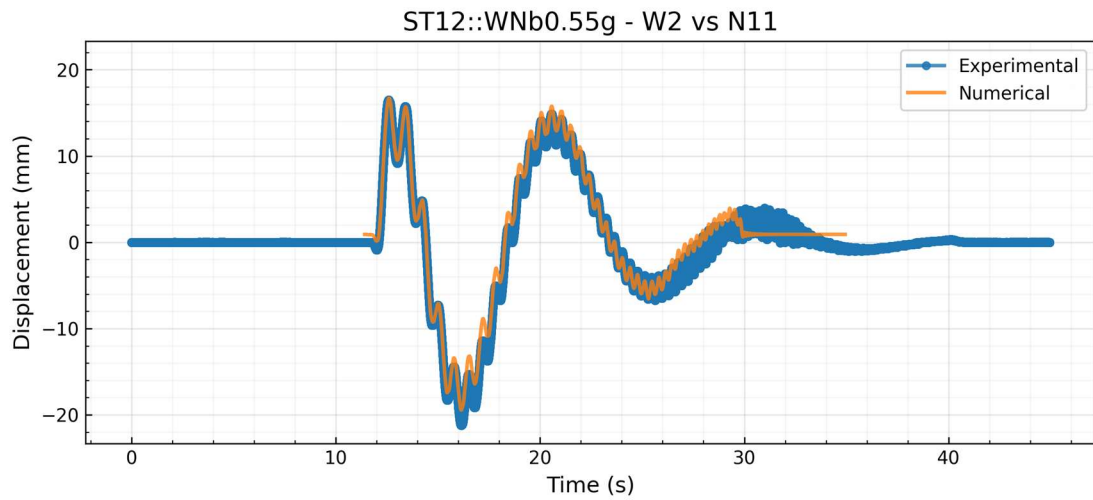


Figure 412 ST12 - Displacement comparison W2 vs N11

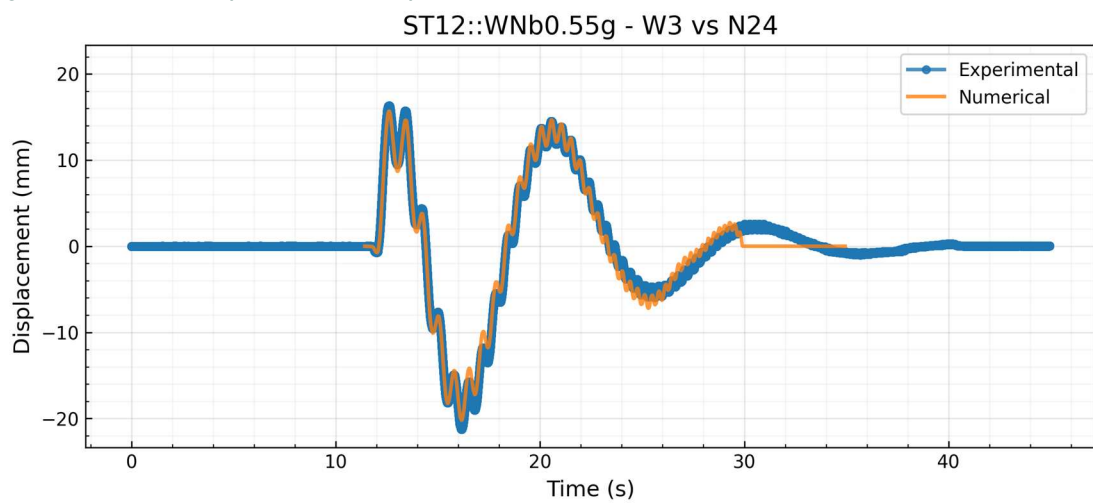


Figure 413 ST12 - Displacement comparison W3 vs N24

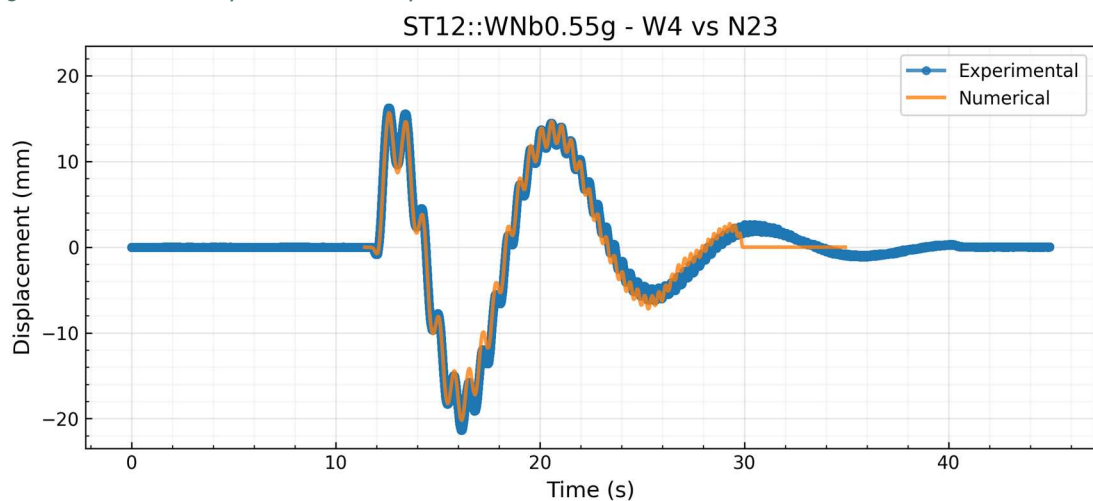


Figure 414 ST12 - Displacement comparison W4 vs N23

6.22 ST14::WNB0.74G RESULTS

The result for draw-wires and accelerometers for ST14::WNB0.74g are presented here.

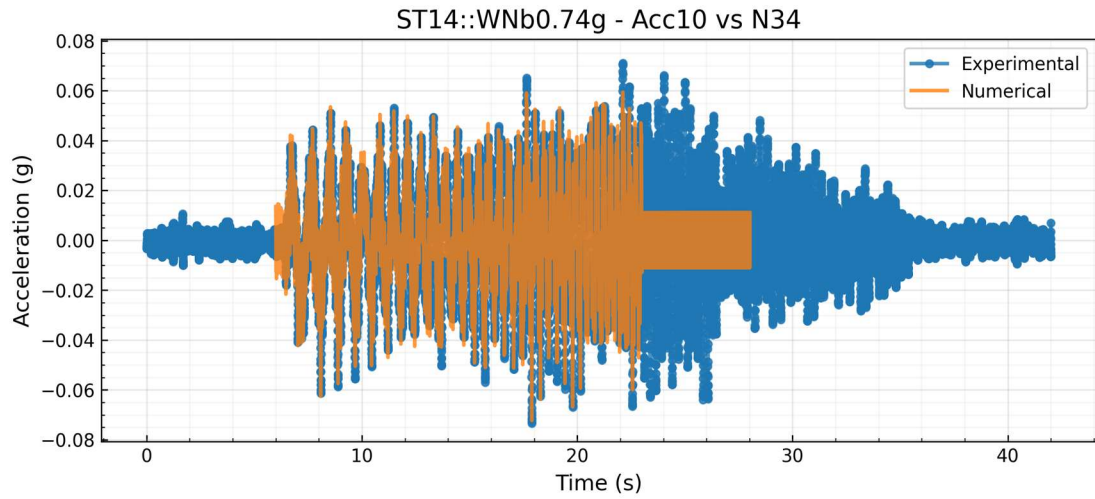


Figure 415 ST14 - Acceleration comparison Acc10 vs N34

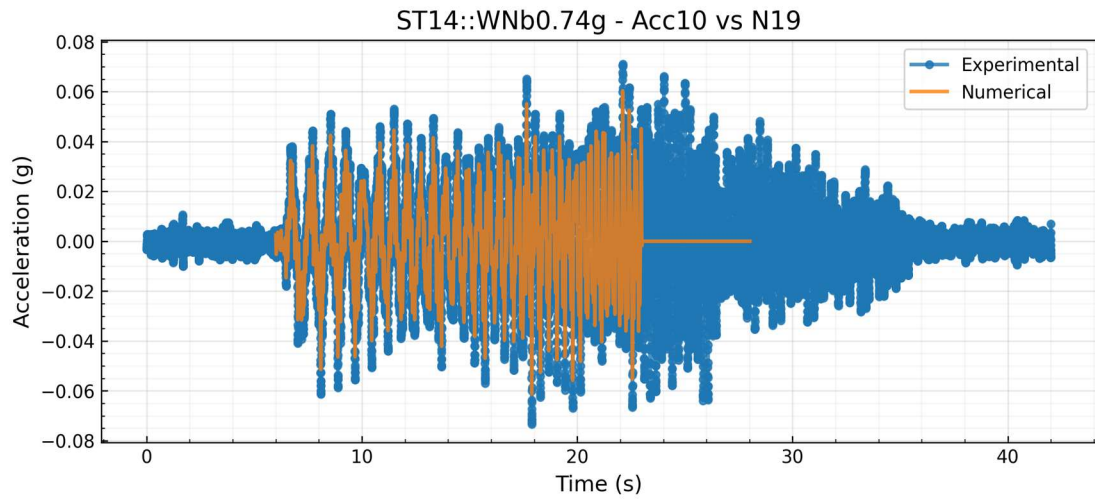


Figure 416 ST14 - Acceleration comparison Acc10 vs N19

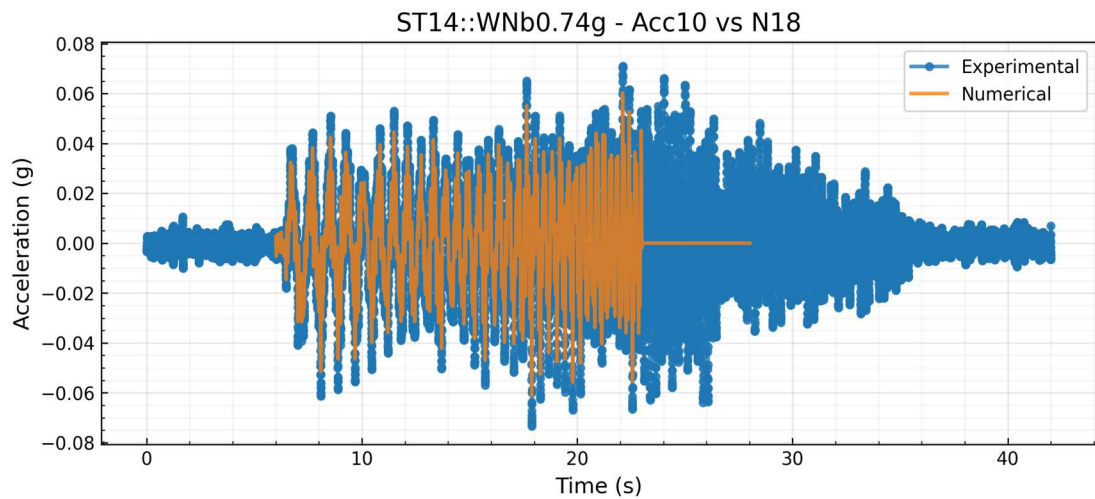


Figure 417 ST14 - Acceleration comparison Acc10 vs N18

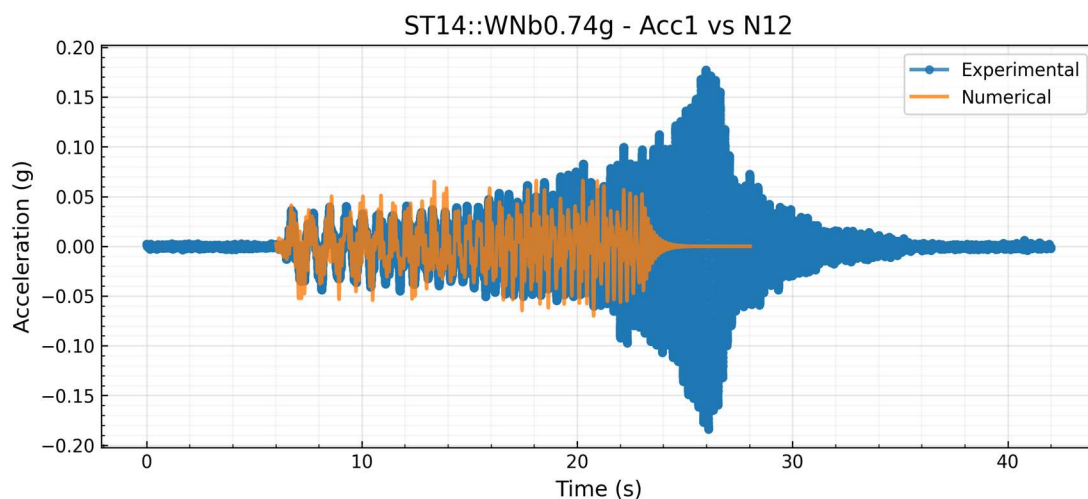


Figure 418 ST14 - Acceleration comparison Acc1 vs N12

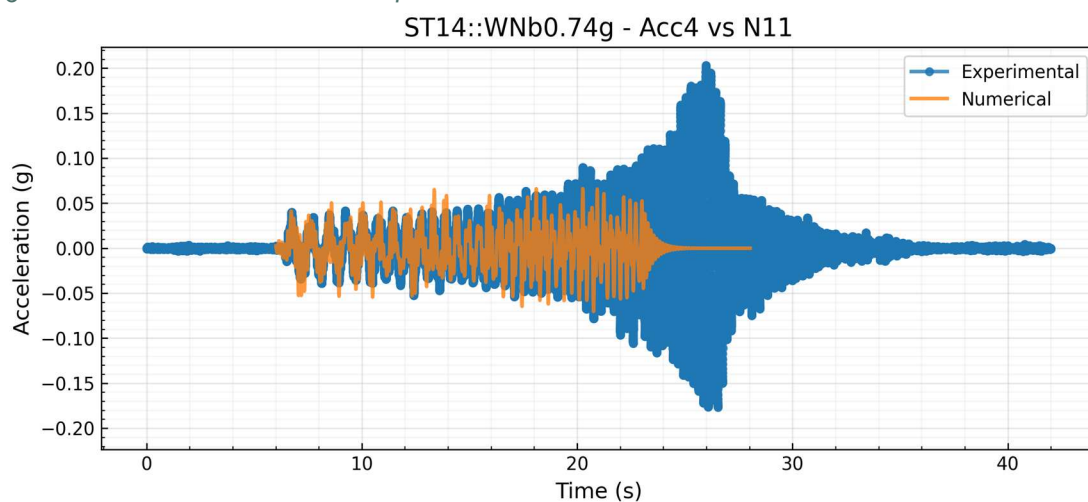


Figure 419 ST14 - Acceleration comparison Acc4 vs N11

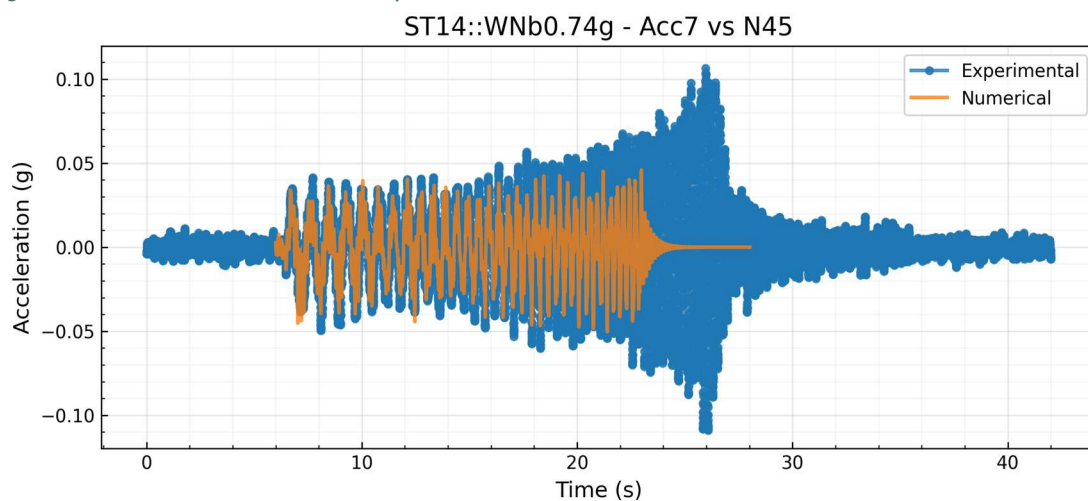


Figure 420 ST14 - Acceleration comparison Acc7 vs N45

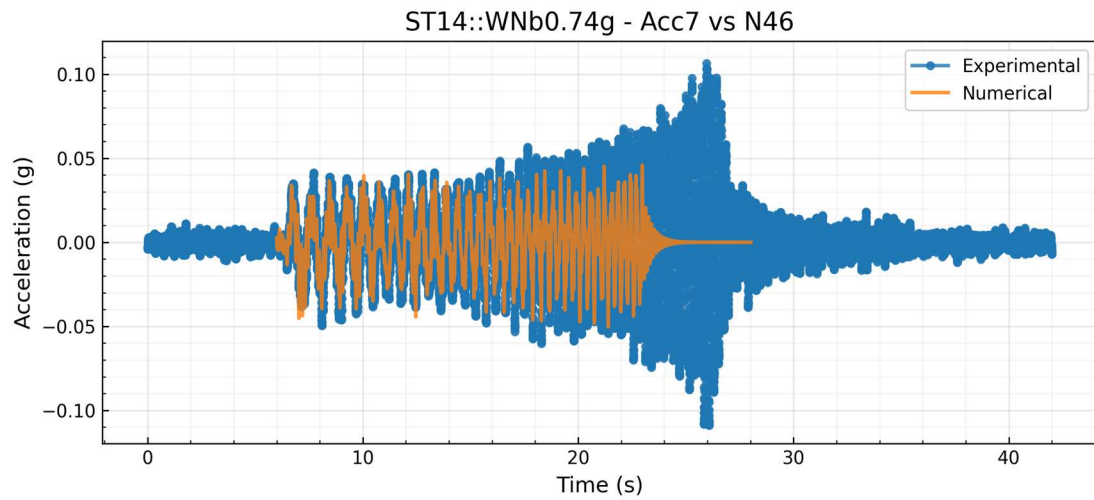


Figure 421 ST14 - Acceleration comparison Acc7 vs N46

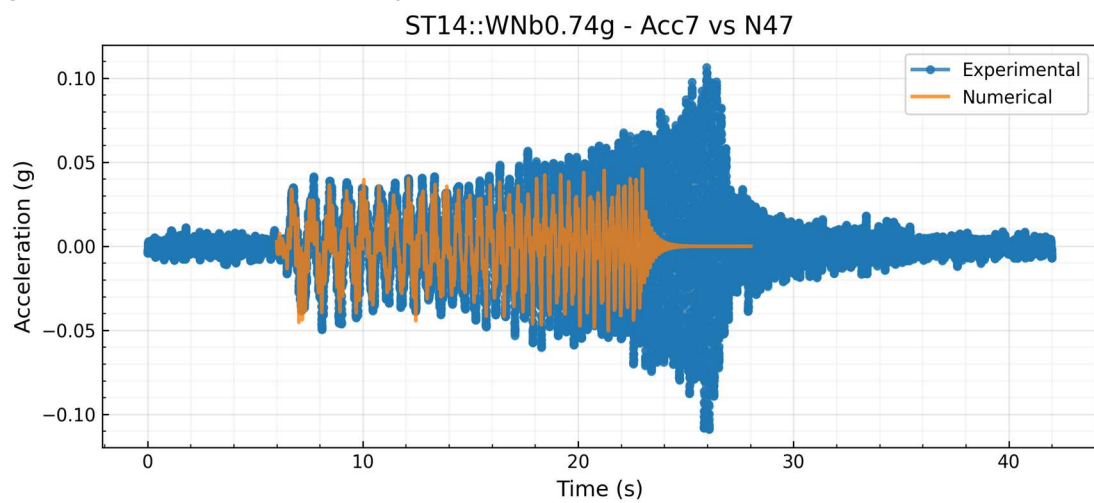


Figure 422 ST14 - Acceleration comparison Acc7 vs N47

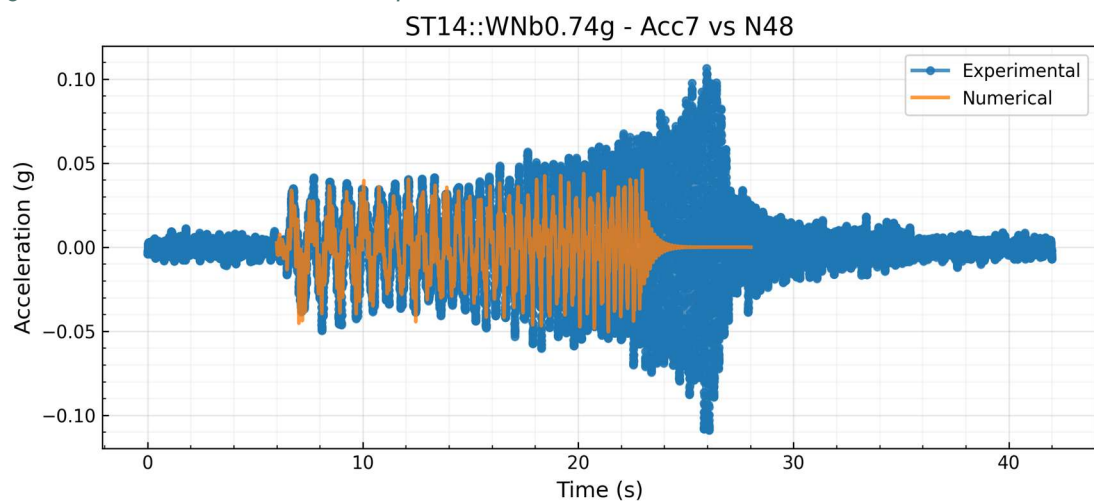


Figure 423 ST14 - Acceleration comparison Acc7 vs N48

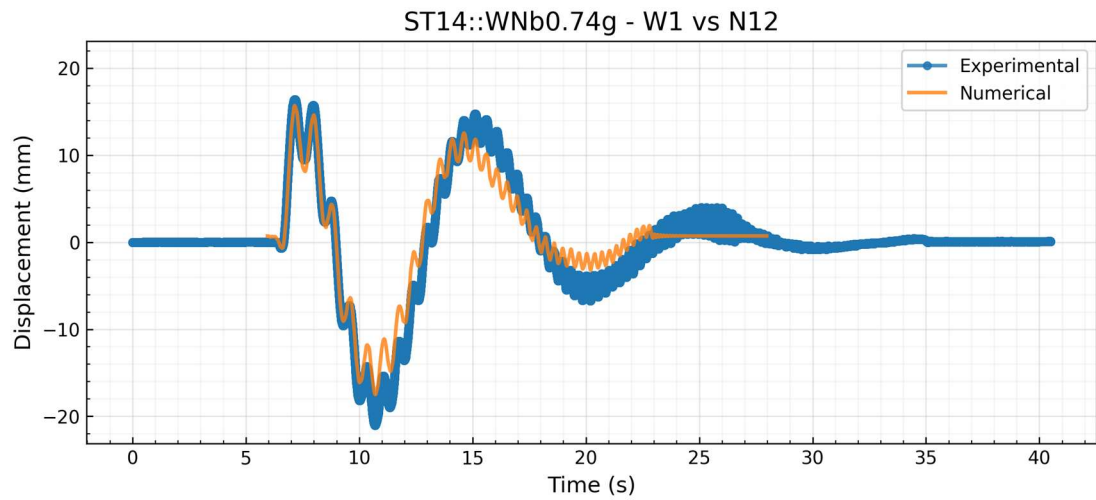


Figure 424 ST14 - Displacement comparison W1 vs N12

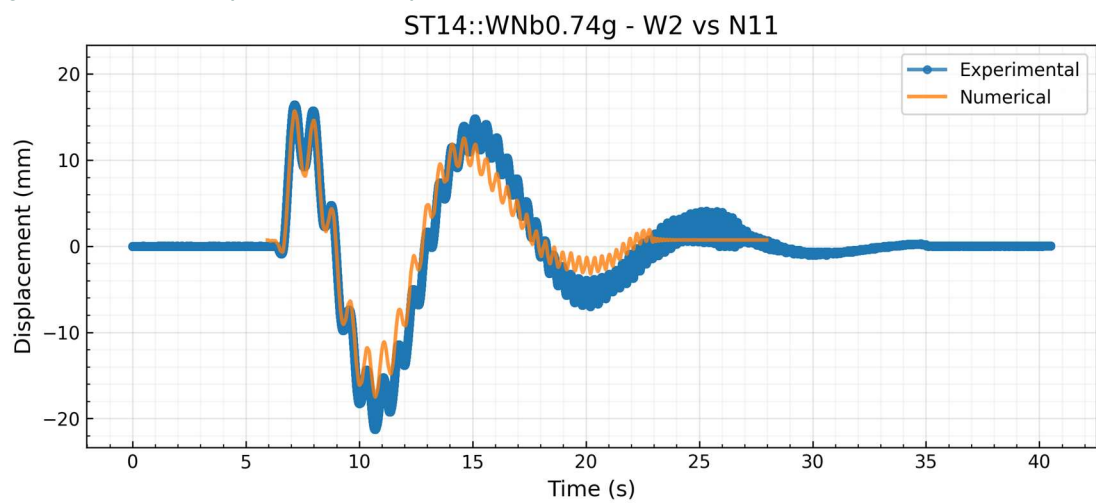


Figure 425 ST14 - Displacement comparison W2 vs N11

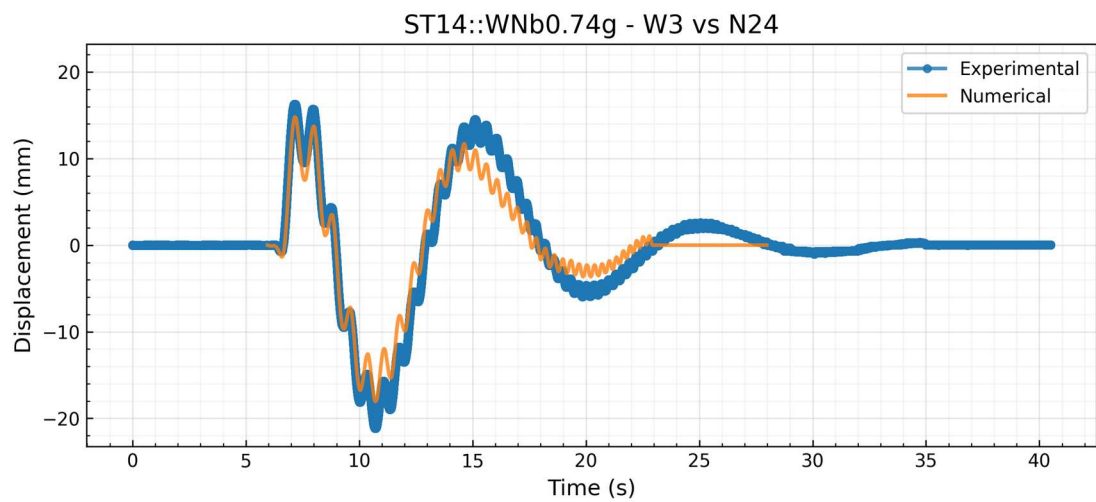


Figure 426 ST14 - Displacement comparison W3 vs N24

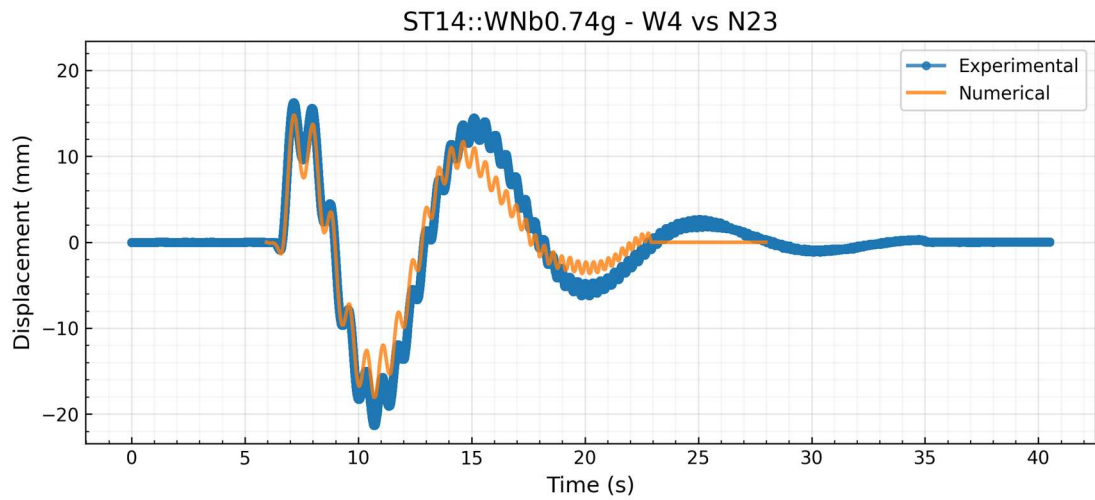


Figure 427 ST14 - Displacement comparison W4 vs N23

6.23 ST16::WNB0.8G RESULTS

The result for draw-wires and accelerometers for ST16::WNB0.8g are presented here.

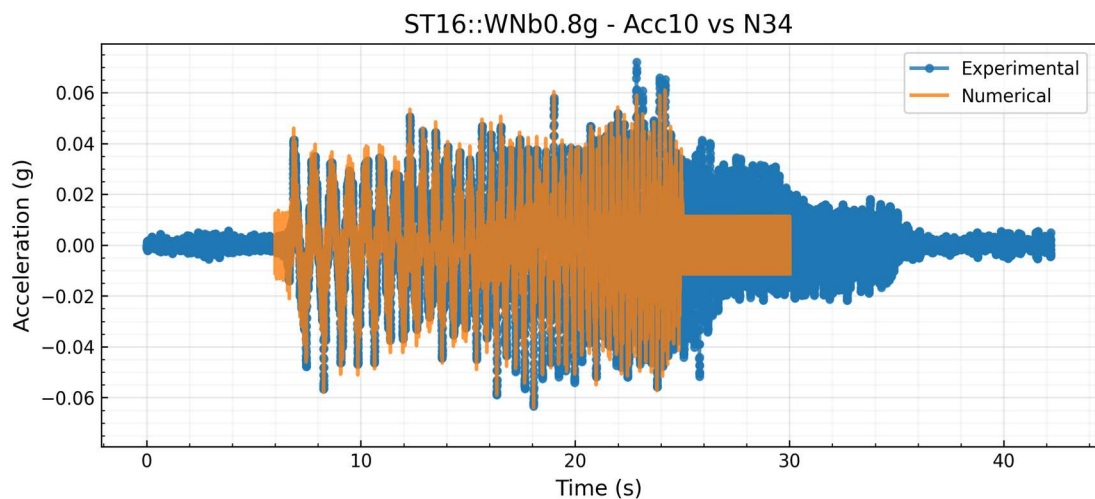


Figure 428 ST16 - Acceleration comparison Acc10 vs N34

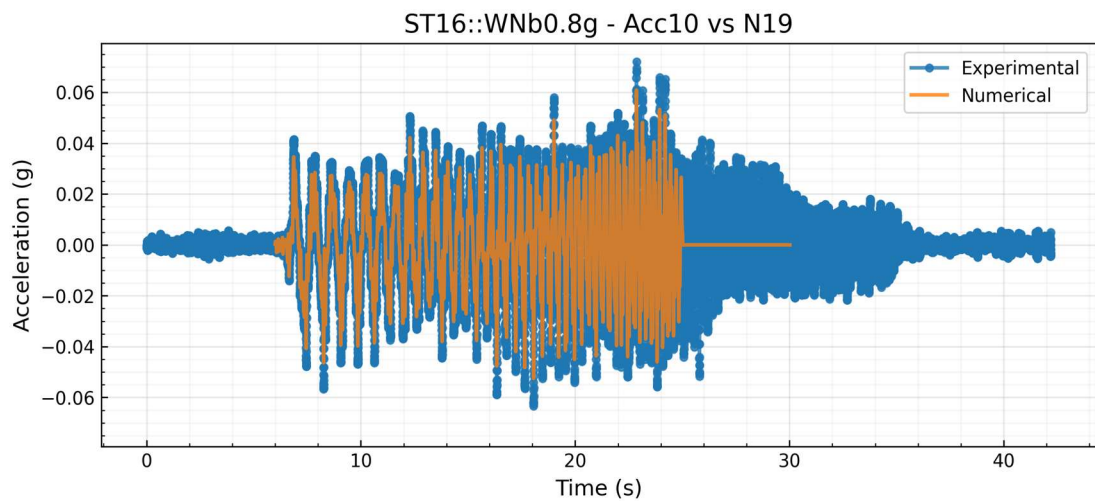


Figure 429 ST16 - Acceleration comparison Acc10 vs N19

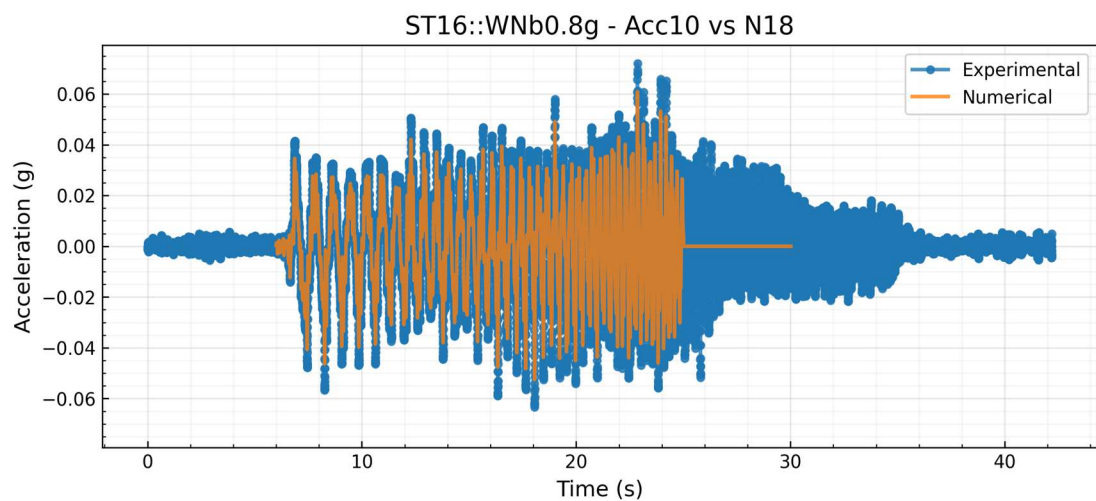


Figure 430 ST16 - Acceleration comparison Acc10 vs N18

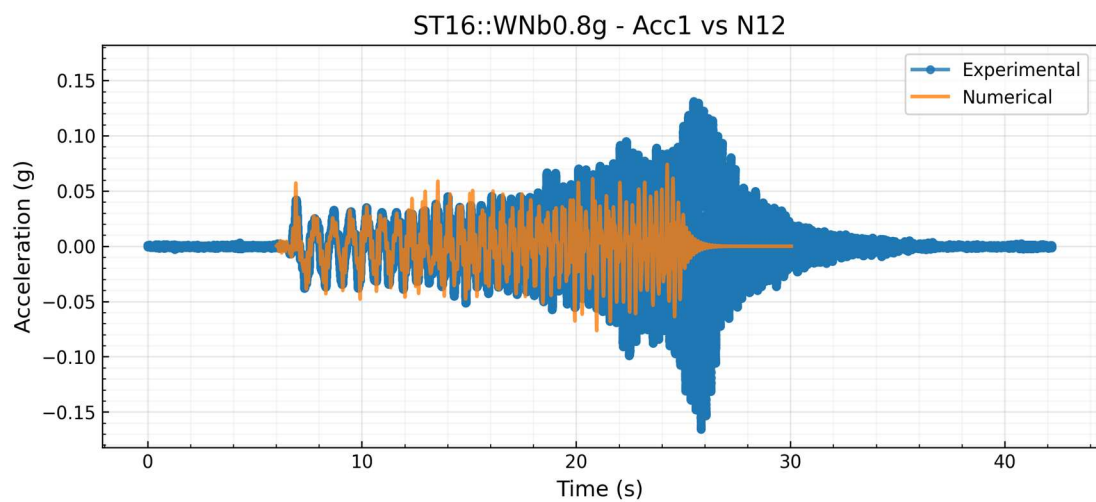


Figure 431 ST16 - Acceleration comparison Acc1 vs N12

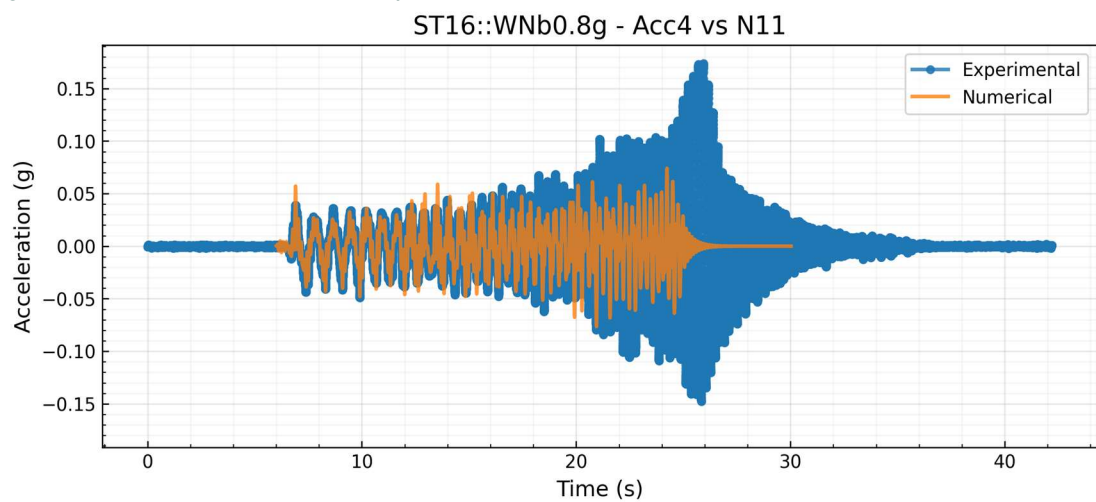


Figure 432 ST16 - Acceleration comparison Acc4 vs N11

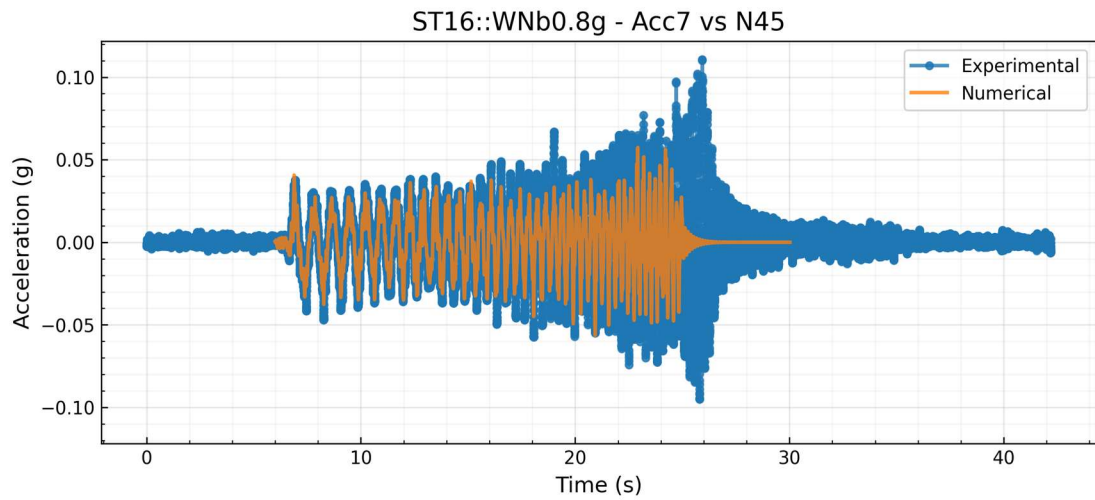


Figure 433 ST16 - Acceleration comparison Acc7 vs N45

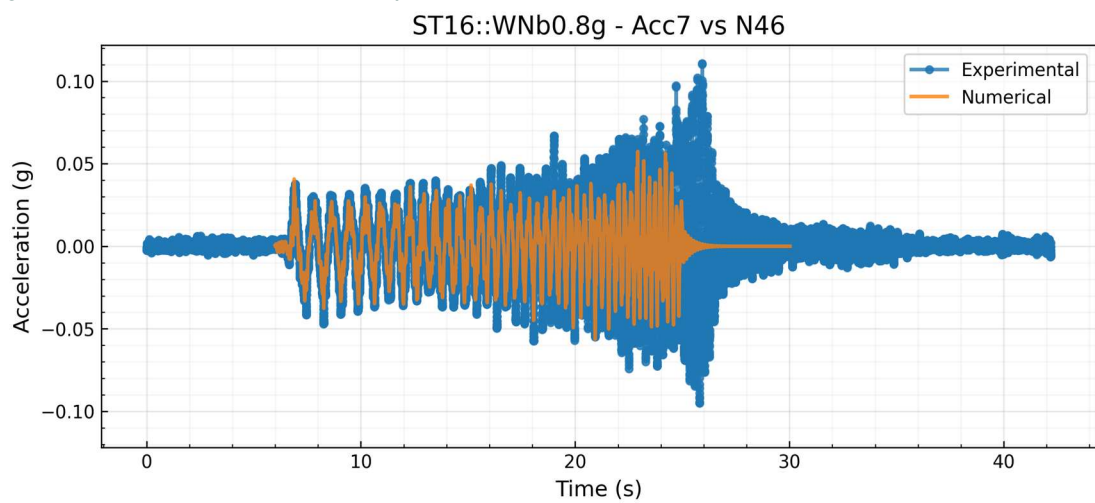


Figure 434 ST16 - Acceleration comparison Acc7 vs N46

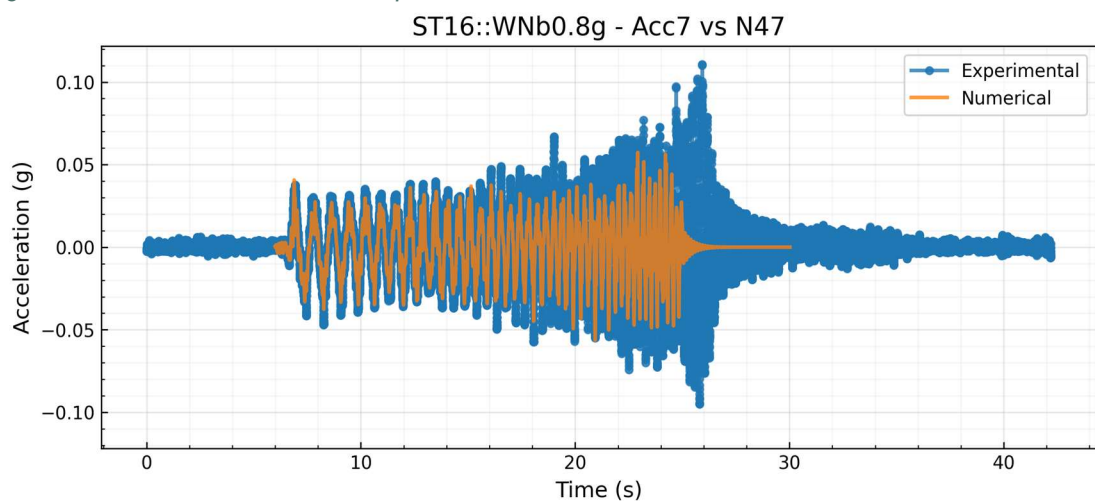


Figure 435 ST16 - Acceleration comparison Acc7 vs N47

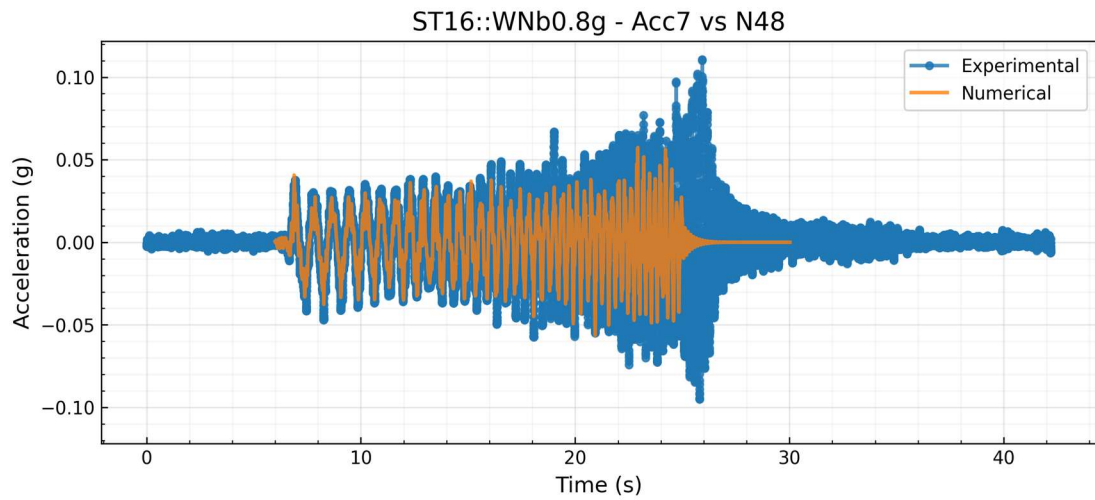


Figure 436 ST16 - Acceleration comparison Acc7 vs N48

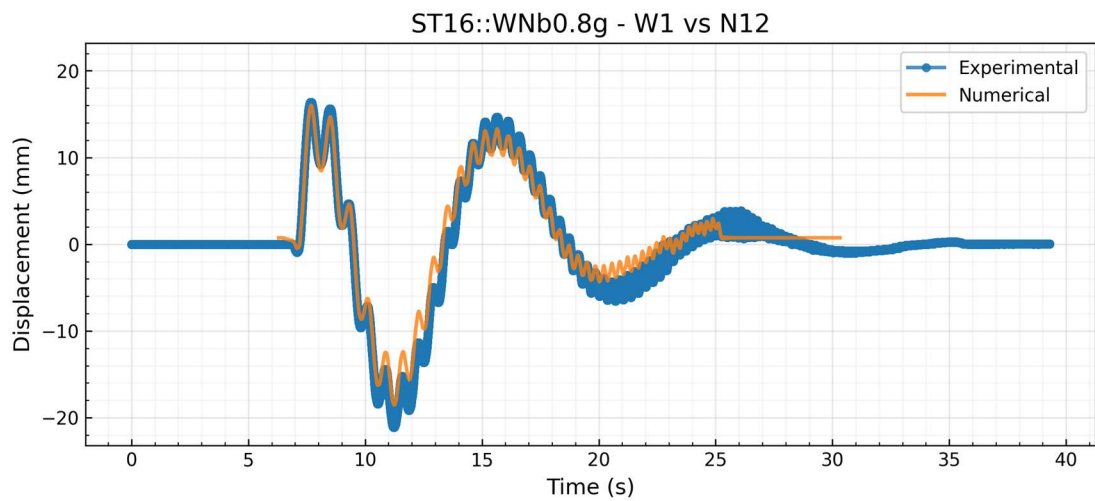


Figure 437 ST16 - Displacement comparison W1 vs N12

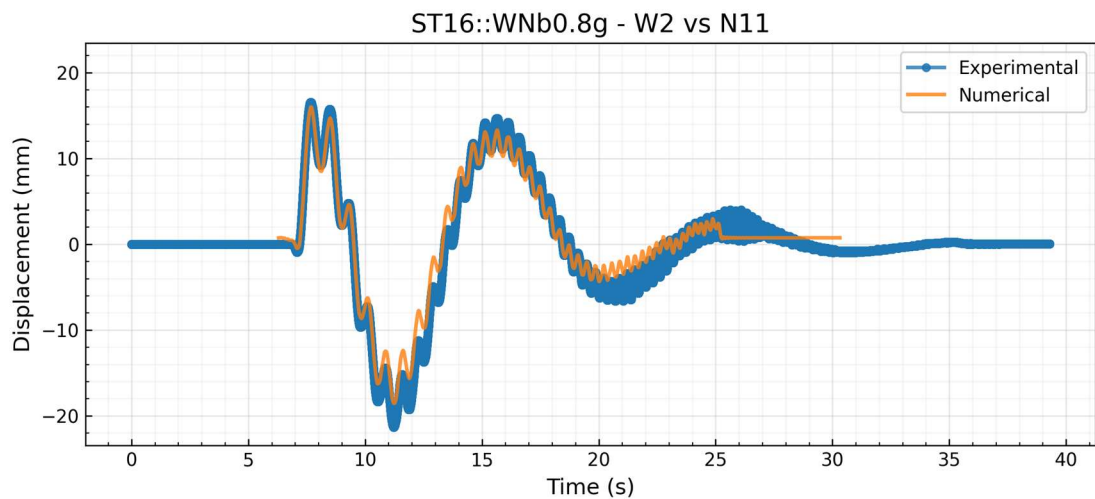


Figure 438 ST16 - Displacement comparison W2 vs N11

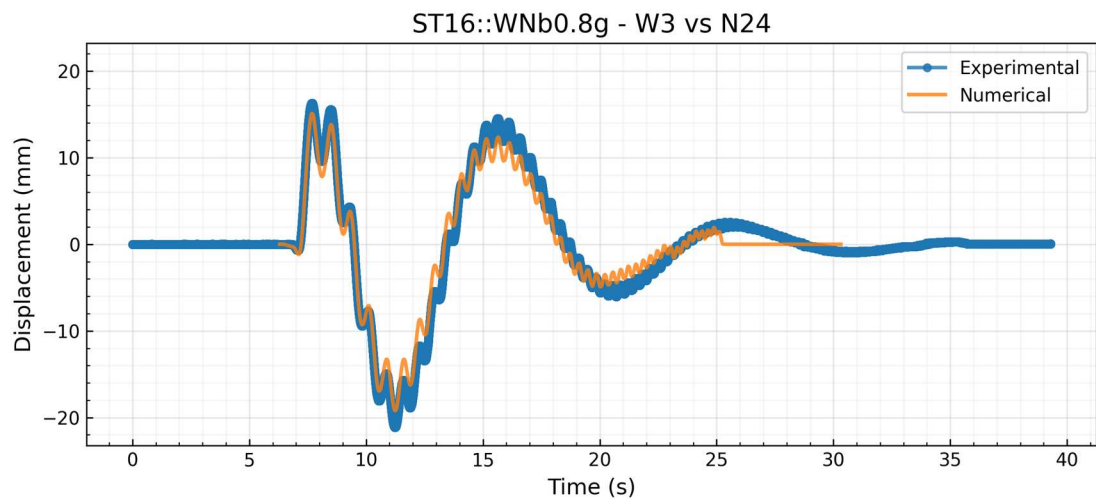


Figure 439 ST16 - Displacement comparison W3 vs N24

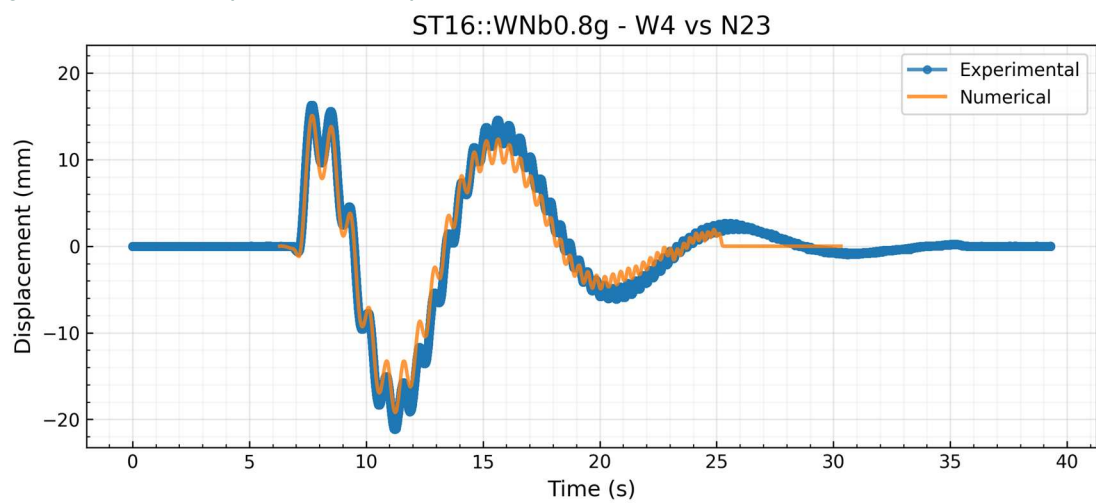


Figure 440 ST16 - Displacement comparison W4 vs N23

6.24 ST18::WNB1.1G RESULTS

The result for draw-wires and accelerometers for ST18::WNB1.1g are presented here.

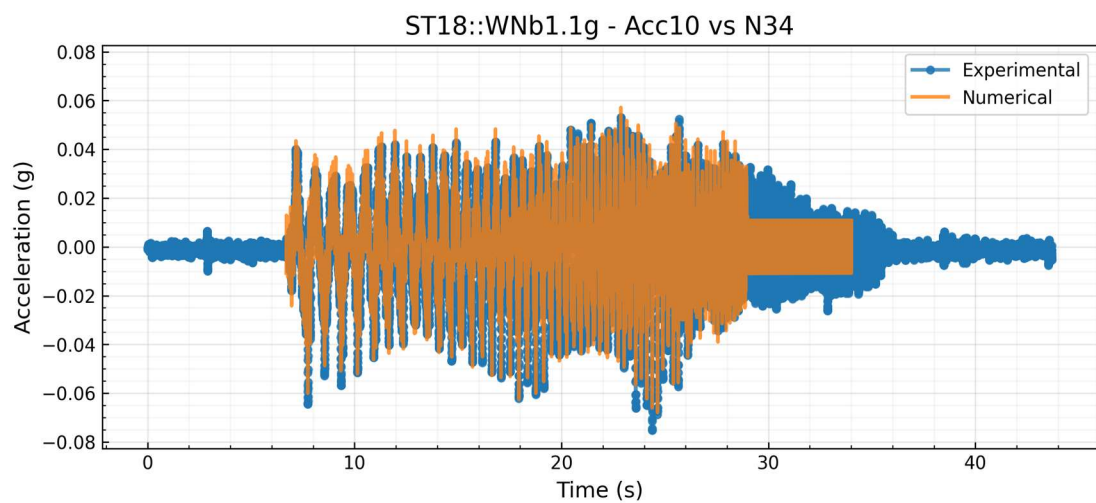


Figure 441 ST18 - Acceleration comparison Acc10 vs N34

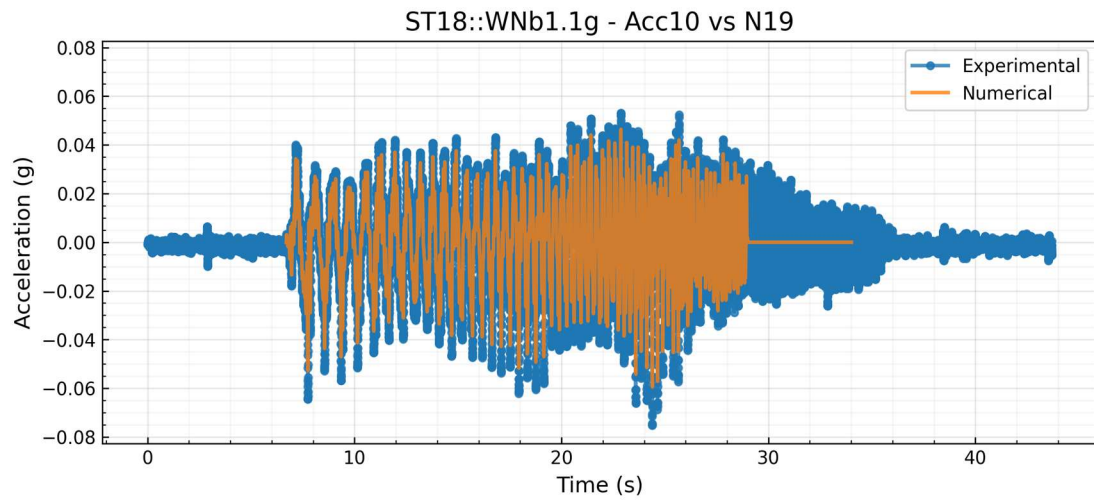


Figure 442 ST18 - Acceleration comparison Acc10 vs N19

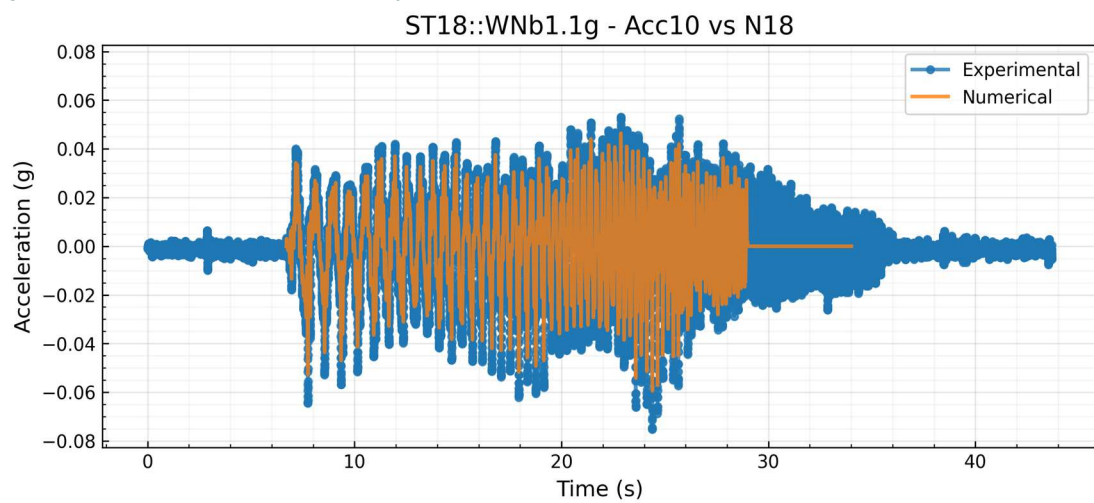


Figure 443 ST18 - Acceleration comparison Acc10 vs N18

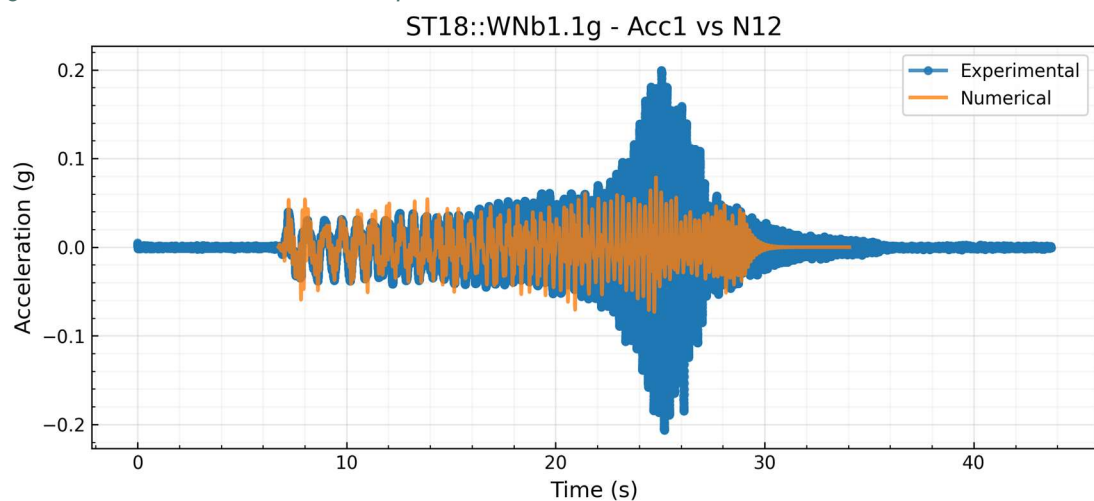


Figure 444 ST18 - Acceleration comparison Acc1 vs N12

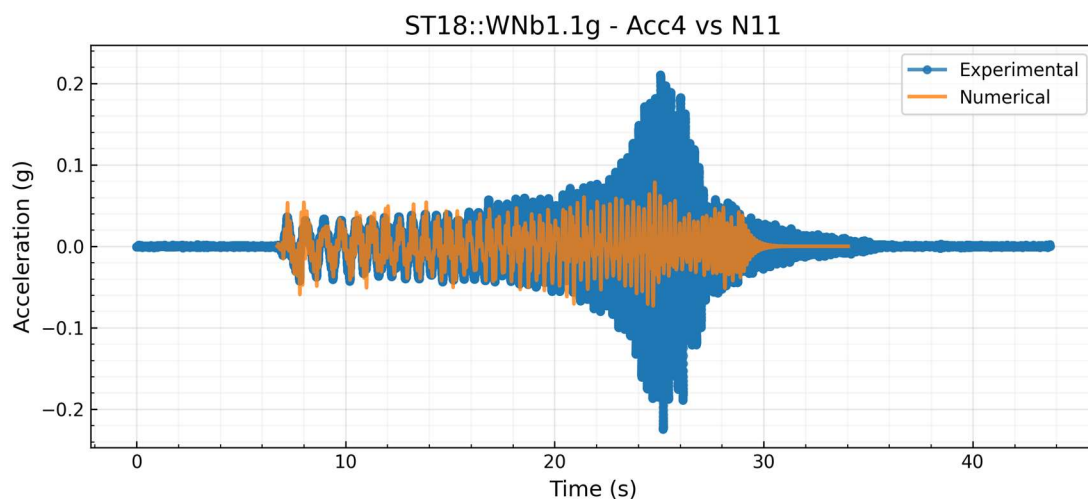


Figure 445 ST18 - Acceleration comparison Acc4 vs N11

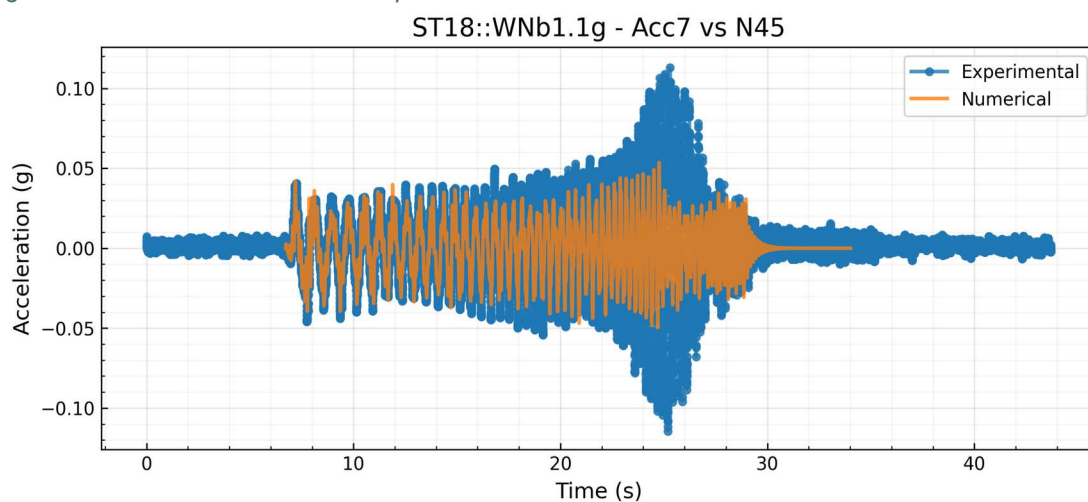


Figure 446 ST18 - Acceleration comparison Acc7 vs N45

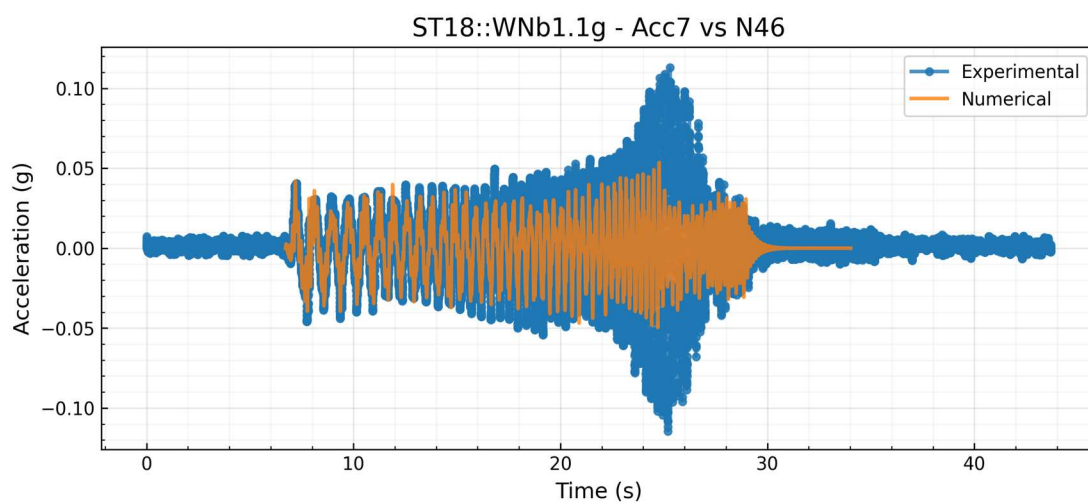


Figure 447 ST18 - Acceleration comparison Acc7 vs N46

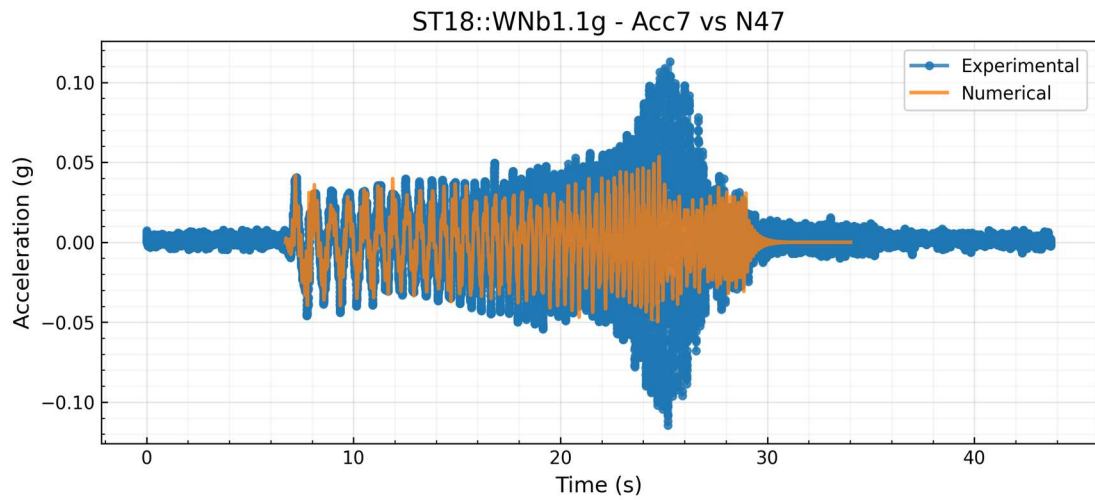


Figure 448 ST18 - Acceleration comparison Acc7 vs N47

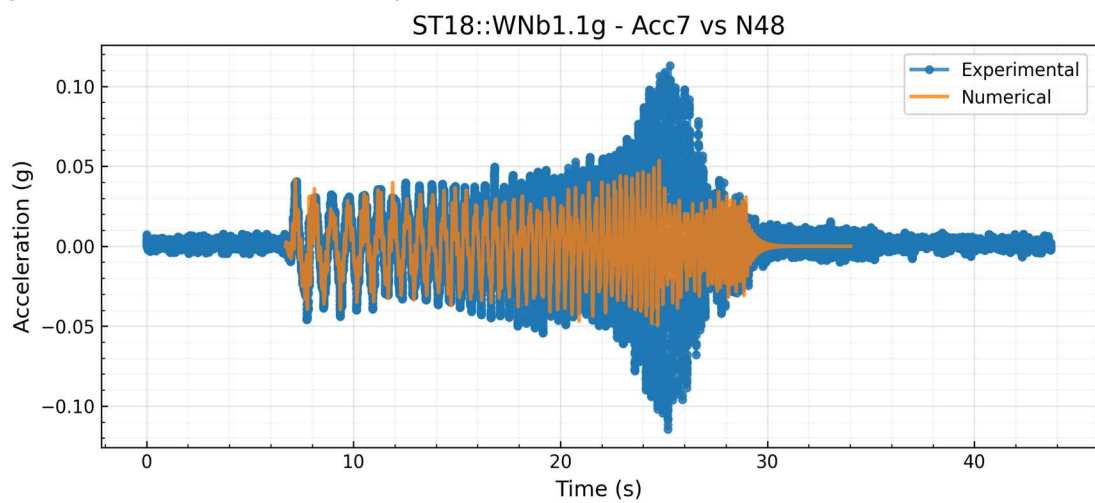


Figure 449 ST18 - Acceleration comparison Acc7 vs N48

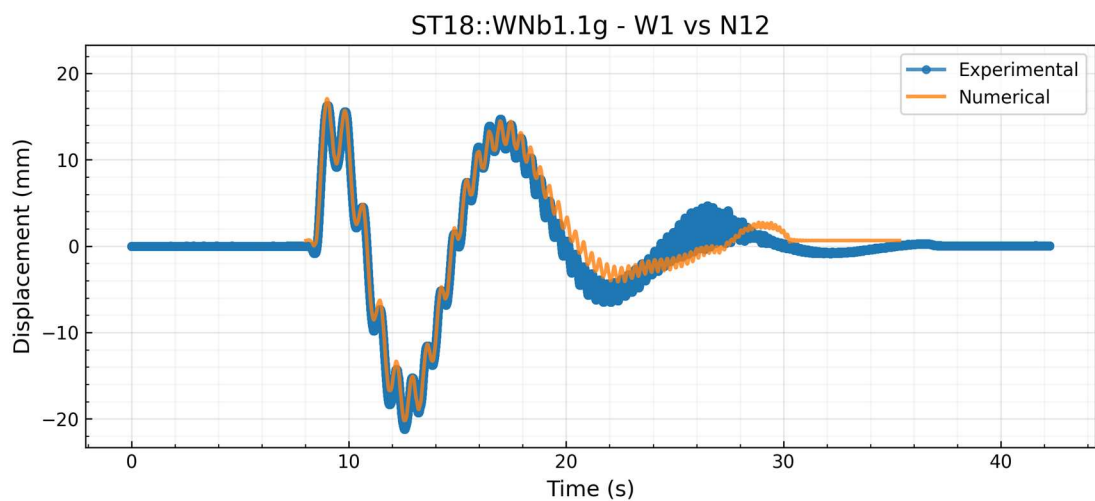


Figure 450 ST18 - Displacement comparison W1 vs N12

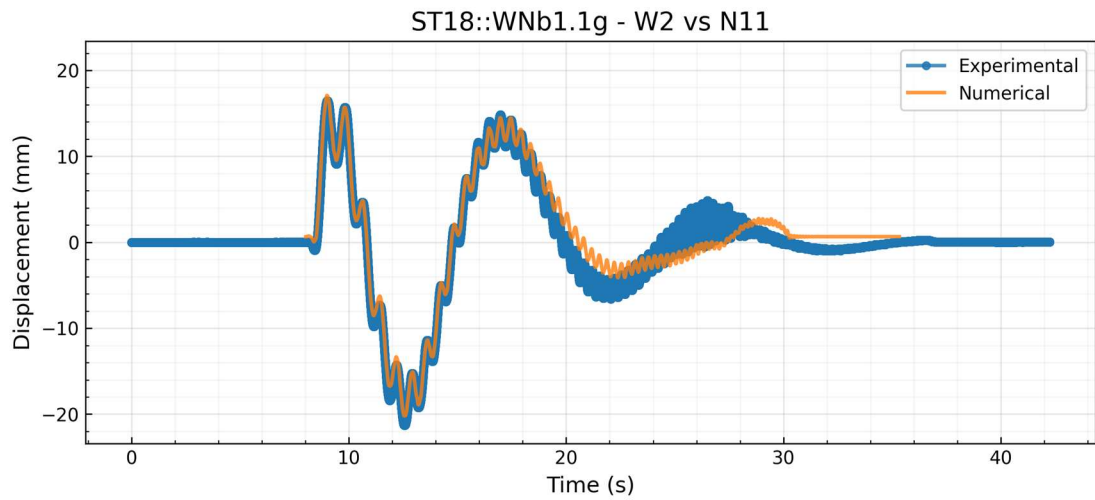


Figure 451 ST18 - Displacement comparison W2 vs N11

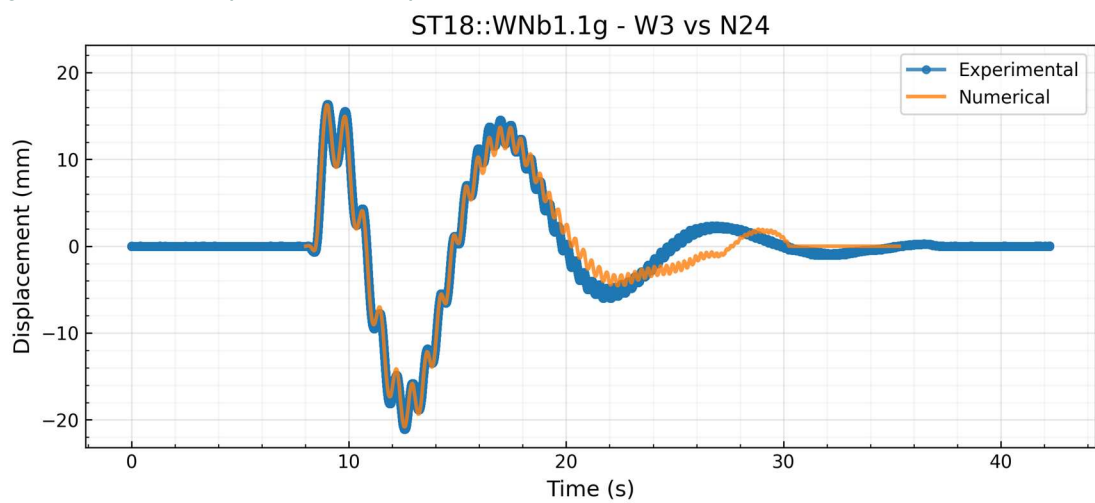


Figure 452 ST18 - Displacement comparison W3 vs N24

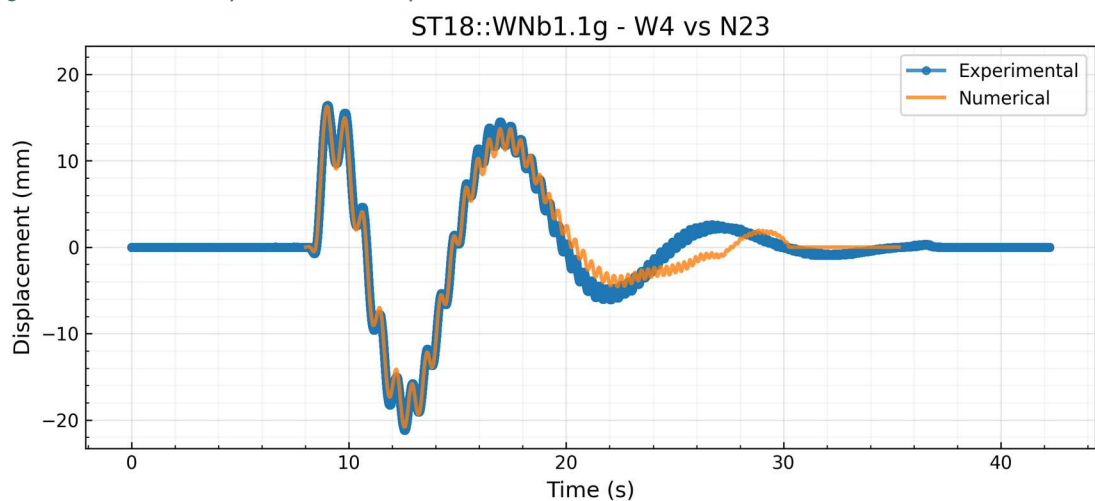


Figure 453 ST18 - Displacement comparison W4 vs N23

6.25 ST20::WNB1.3G RESULTS

The result for draw-wires and accelerometers for ST20::WNB1.3g are presented here.

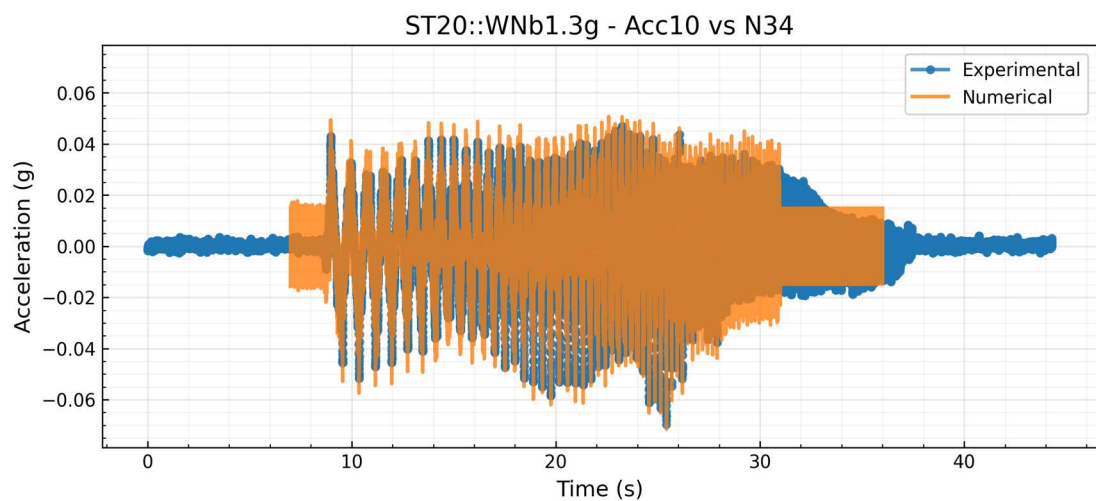


Figure 454 ST20 - Acceleration comparison Acc10 vs N34

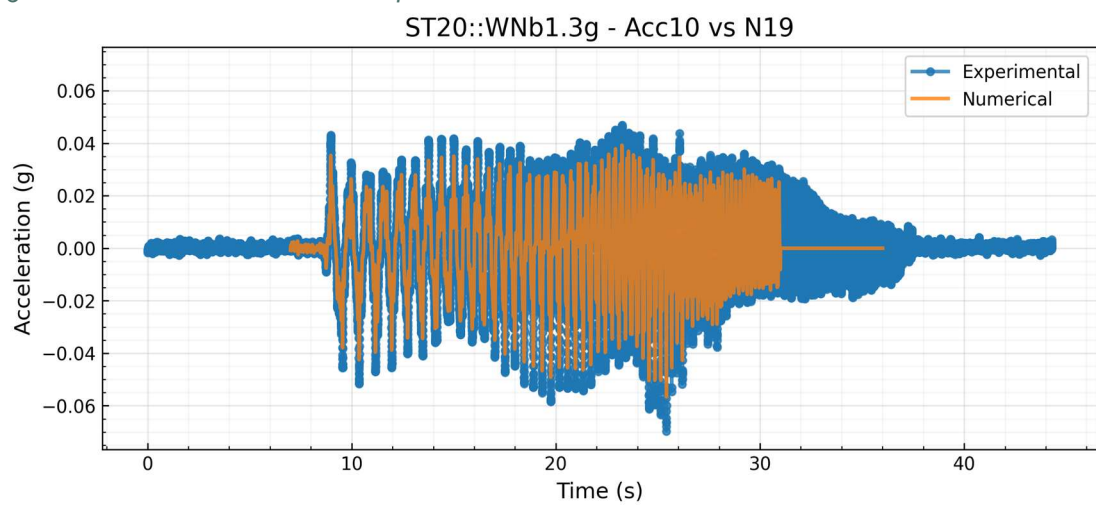


Figure 455 ST20 - Acceleration comparison Acc10 vs N19

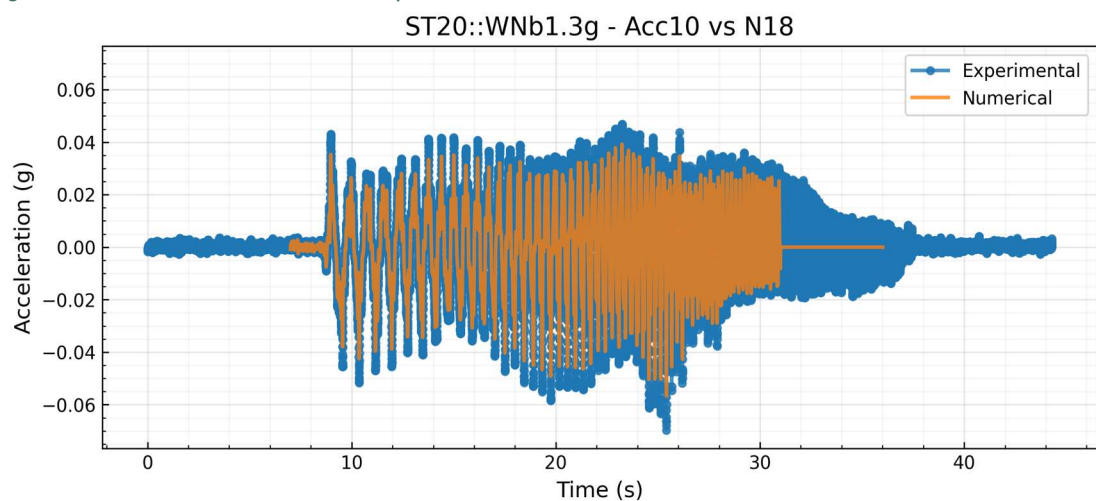


Figure 456 ST20 - Acceleration comparison Acc10 vs N18

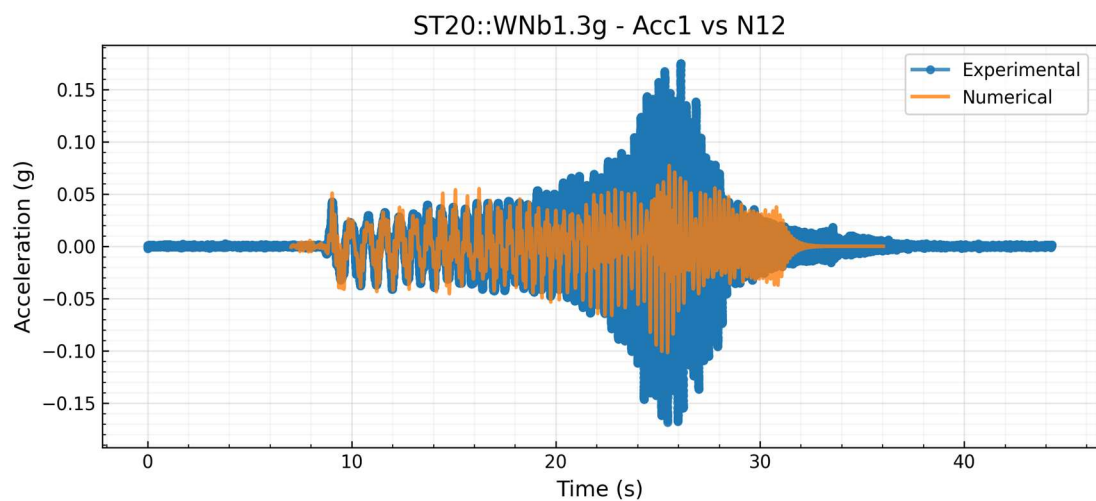


Figure 457 ST20 - Acceleration comparison Acc1 vs N12

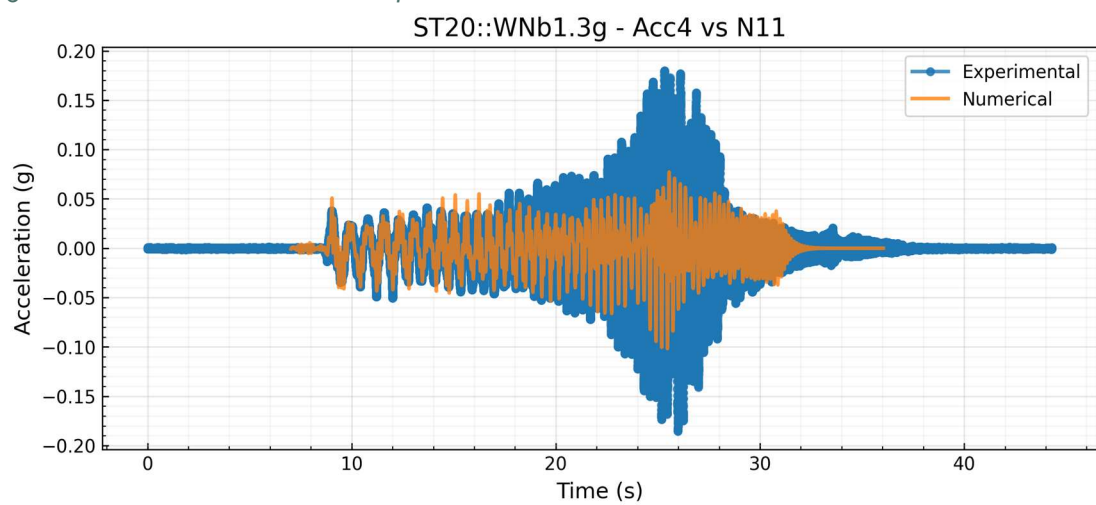


Figure 458 ST20 - Acceleration comparison Acc4 vs N11

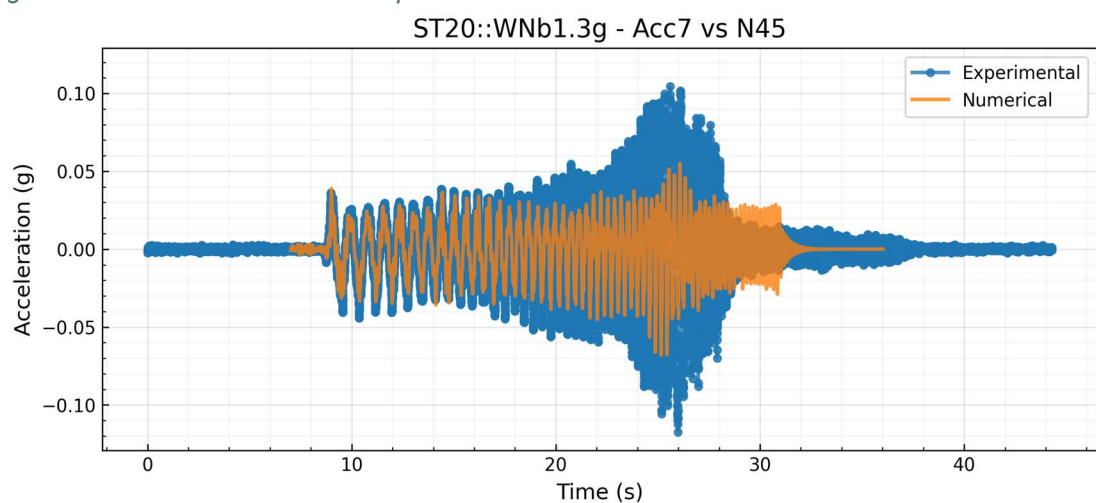


Figure 459 ST20 - Acceleration comparison Acc7 vs N45

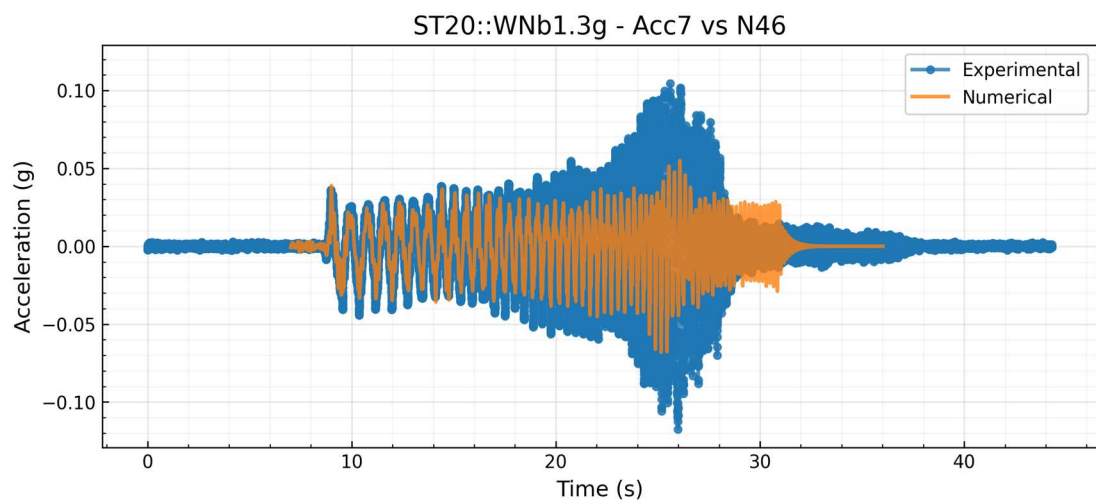


Figure 460 ST20 - Acceleration comparison Acc7 vs N46

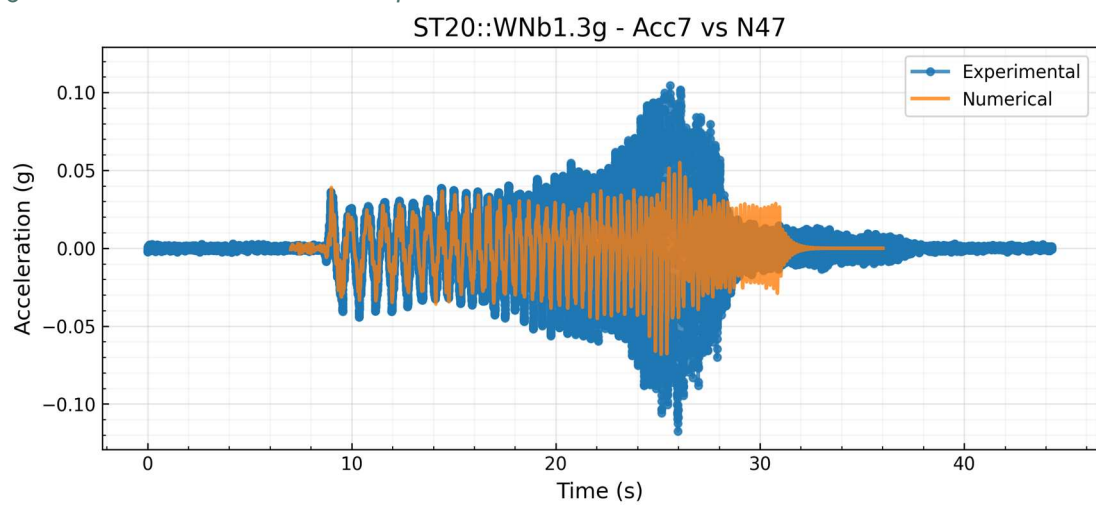


Figure 461 ST20 - Acceleration comparison Acc7 vs N47

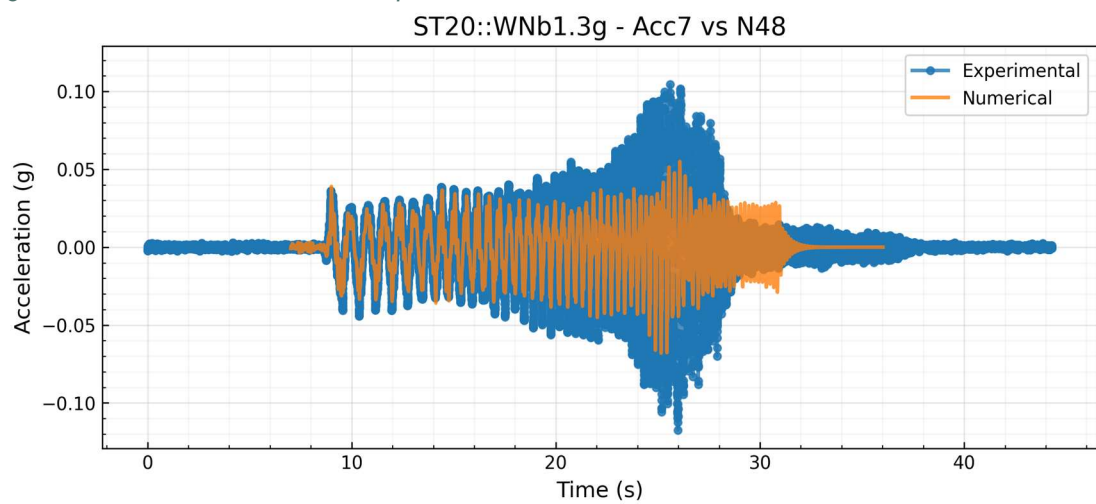


Figure 462 ST20 - Acceleration comparison Acc7 vs N48

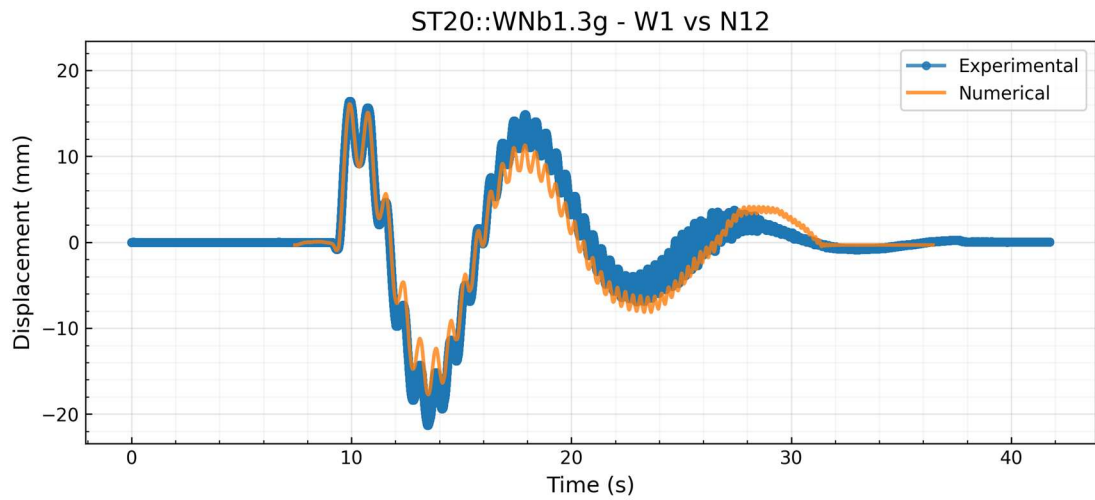


Figure 463 ST20 - Displacement comparison W1 vs N12

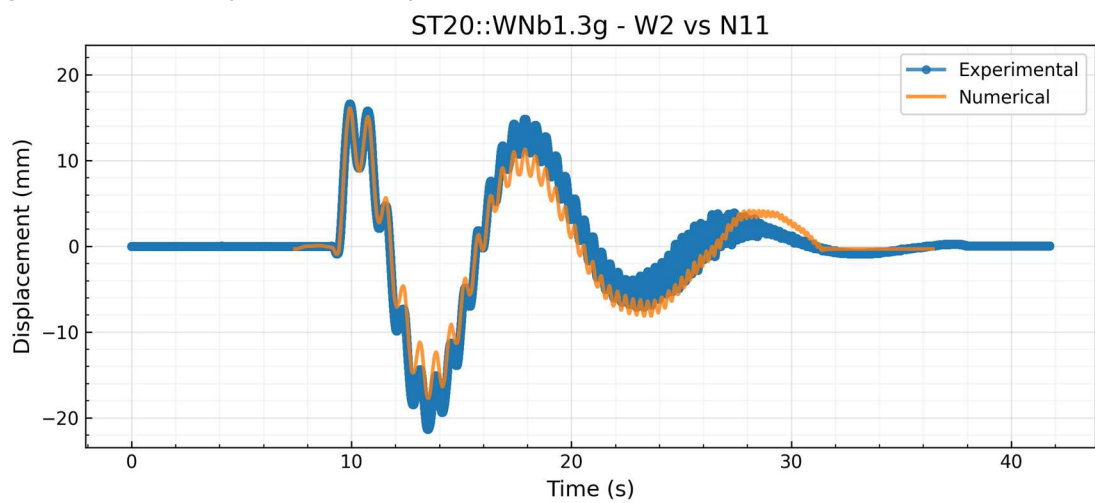


Figure 464 ST20 - Displacement comparison W2 vs N11

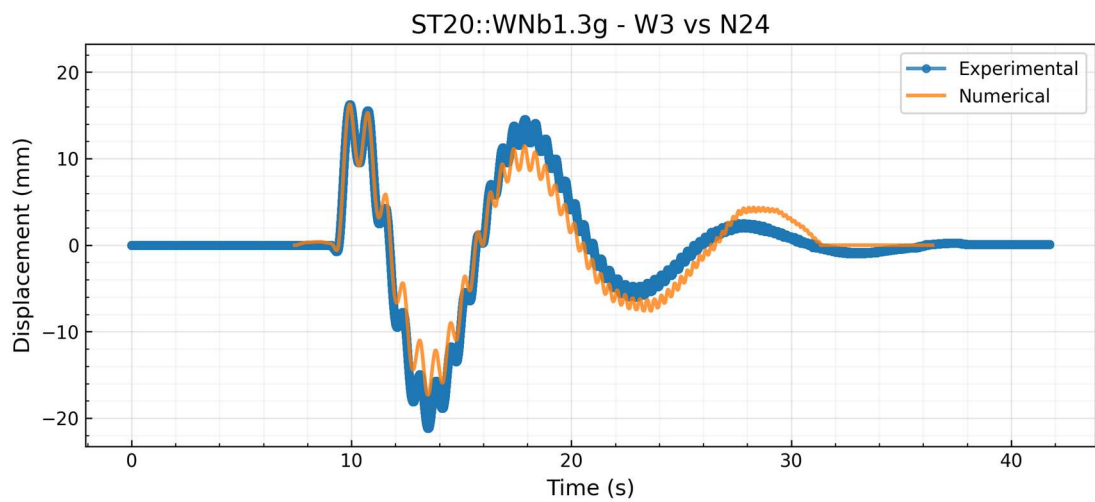


Figure 465 ST20 - Displacement comparison W3 vs N24

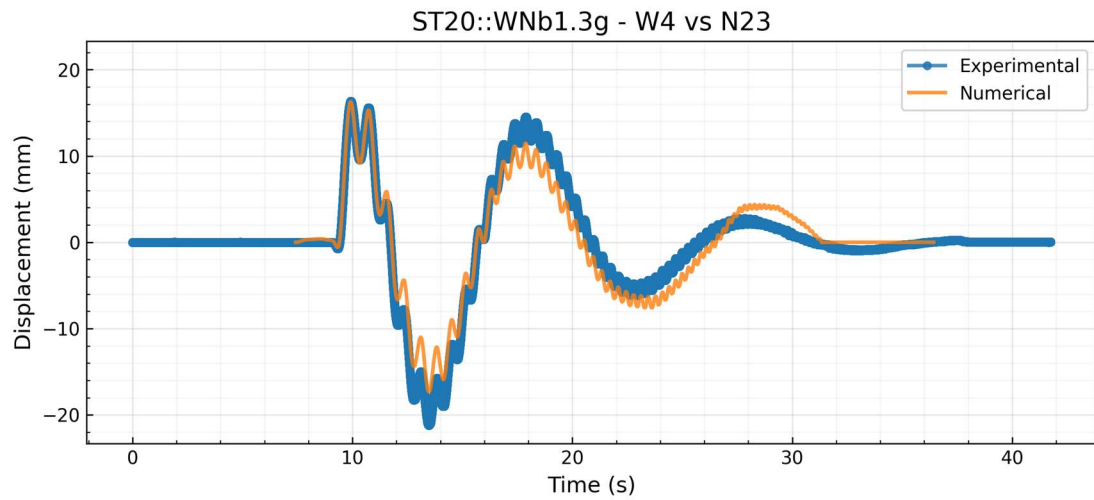


Figure 466 ST20 - Displacement comparison W4 vs N23

6.26 ST24::WNB1.4G RESULTS

The result for draw-wires and accelerometers for ST24::WNB1.4g are presented here.

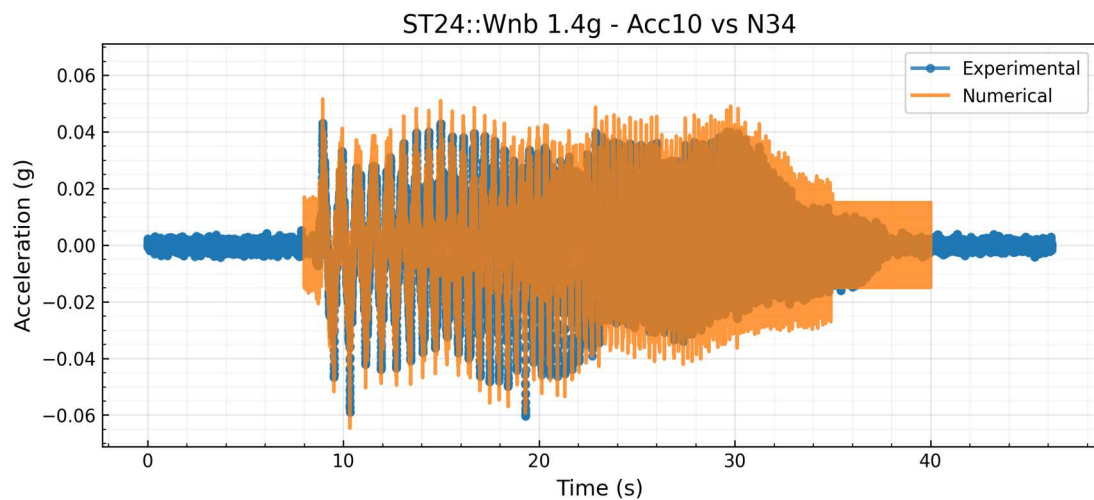


Figure 467 ST24 - Acceleration comparison Acc10 vs N34

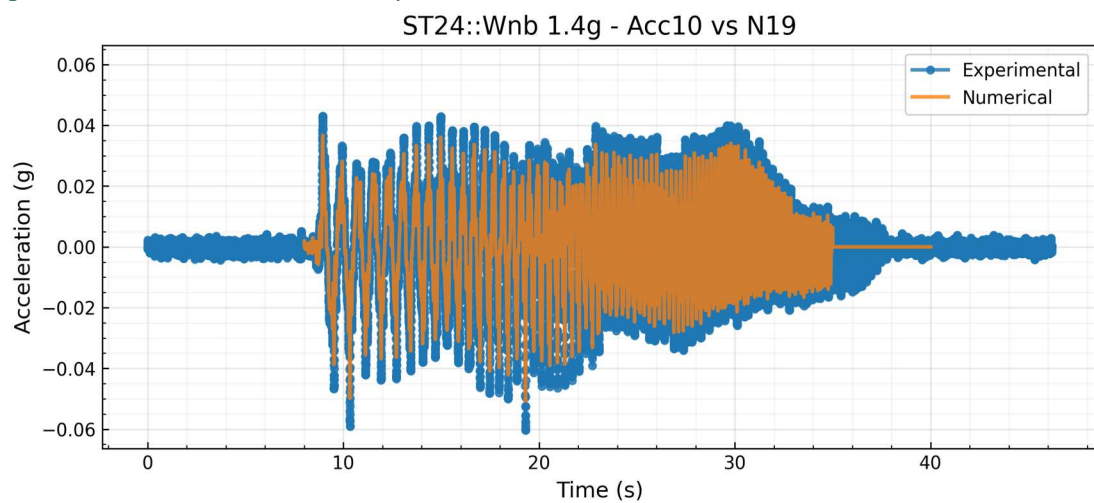


Figure 468 ST24 - Acceleration comparison Acc10 vs N19

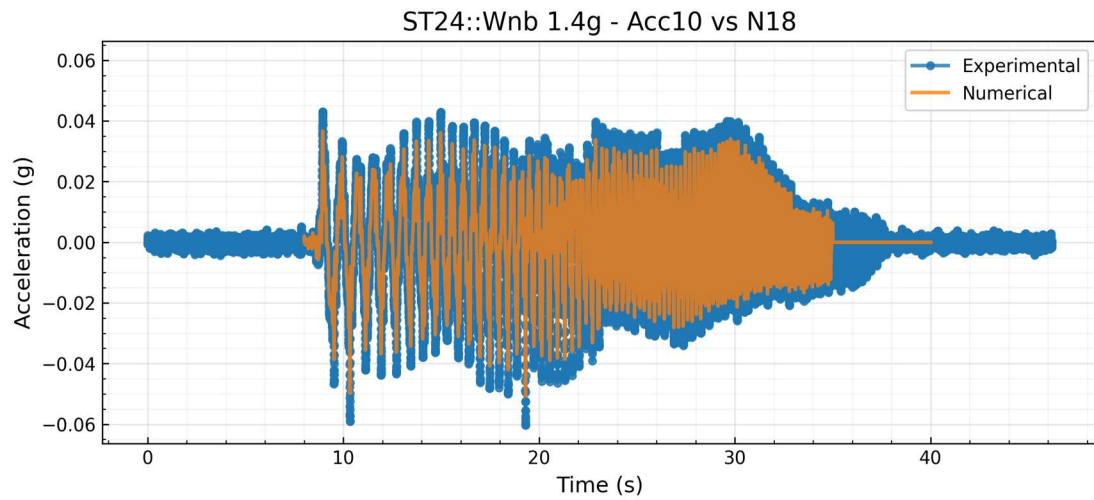


Figure 469 ST24 - Acceleration comparison Acc10 vs N18

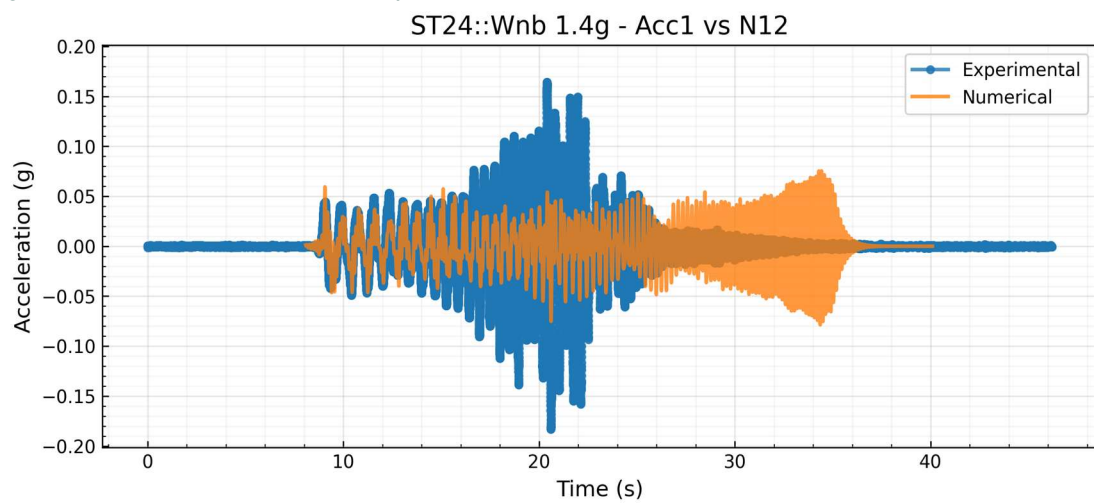


Figure 470 ST24 - Acceleration comparison Acc1 vs N12

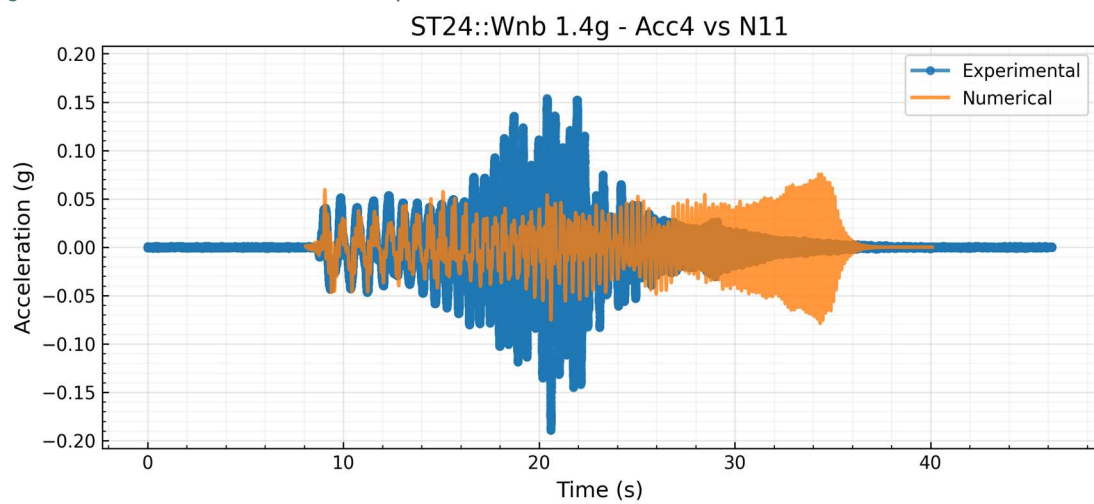


Figure 471 ST24 - Acceleration comparison Acc4 vs N11

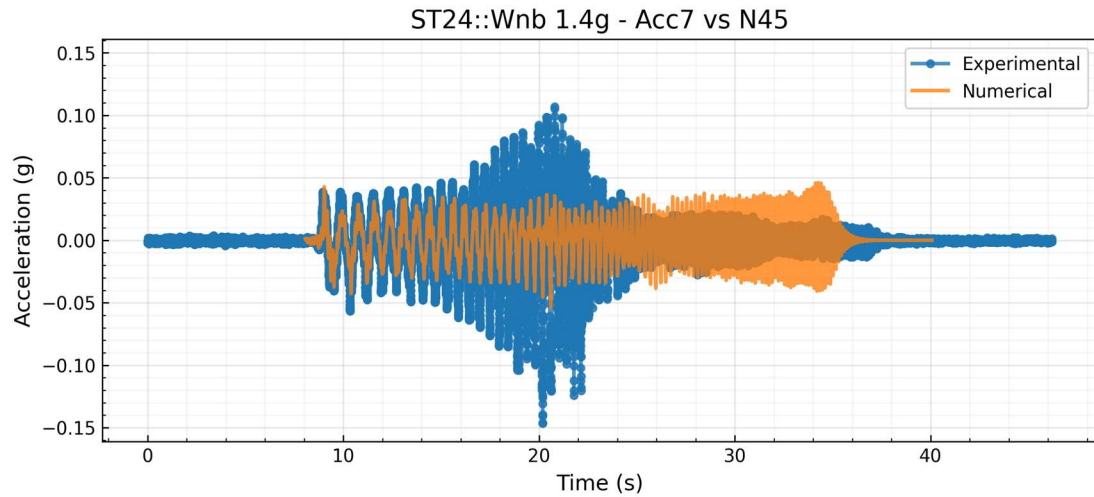


Figure 472 ST24 - Acceleration comparison Acc7 vs N45

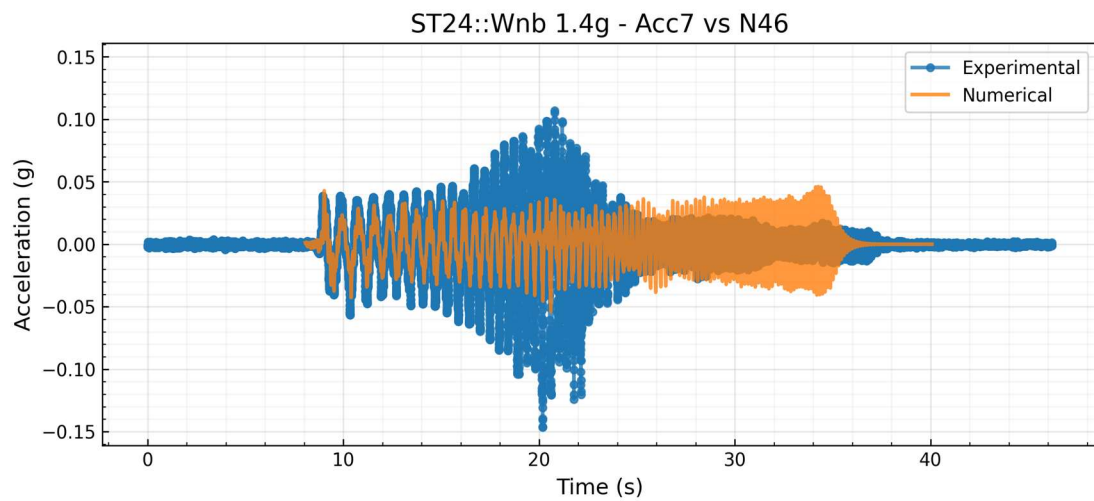


Figure 473 ST24 - Acceleration comparison Acc7 vs N46

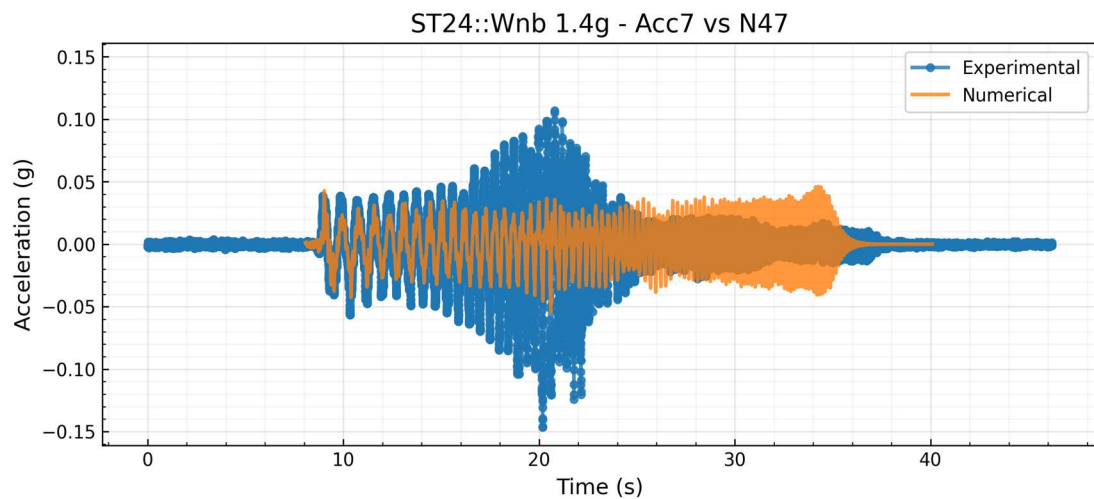


Figure 474 ST24 - Acceleration comparison Acc7 vs N47

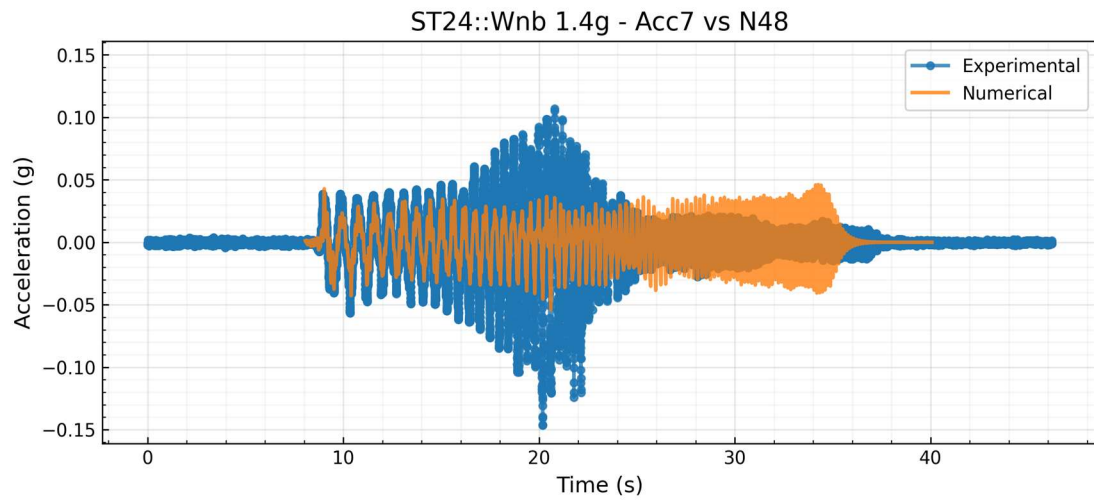


Figure 475 ST24 - Acceleration comparison Acc7 vs N48

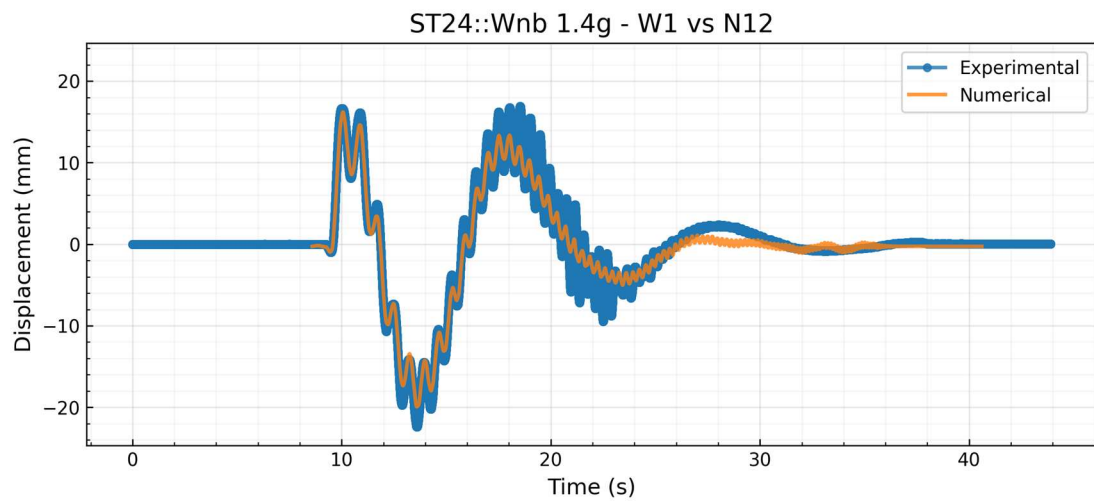


Figure 476 ST24 - Displacement comparison W1 vs N12

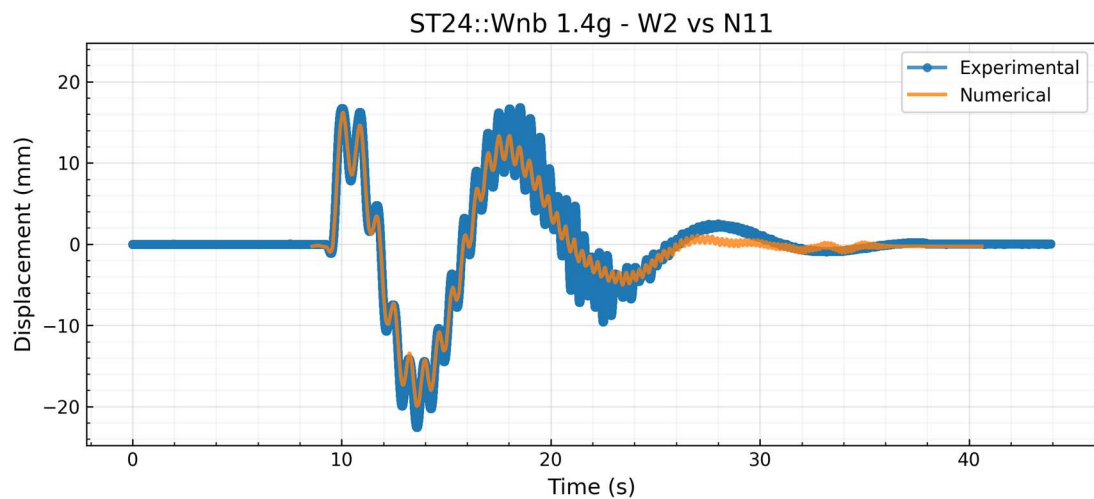


Figure 477 ST24 - Displacement comparison W2 vs N11

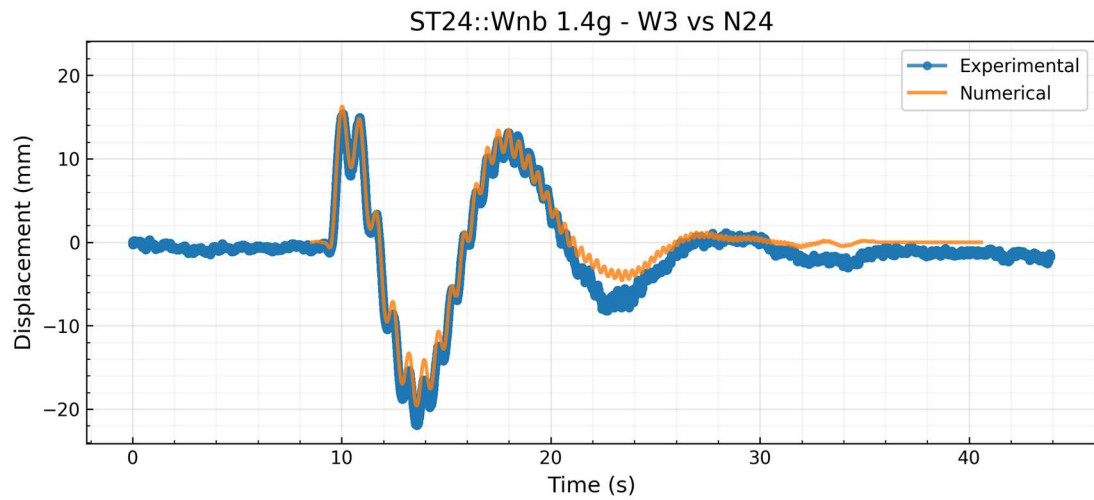


Figure 478 ST24 - Displacement comparison W3 vs N24

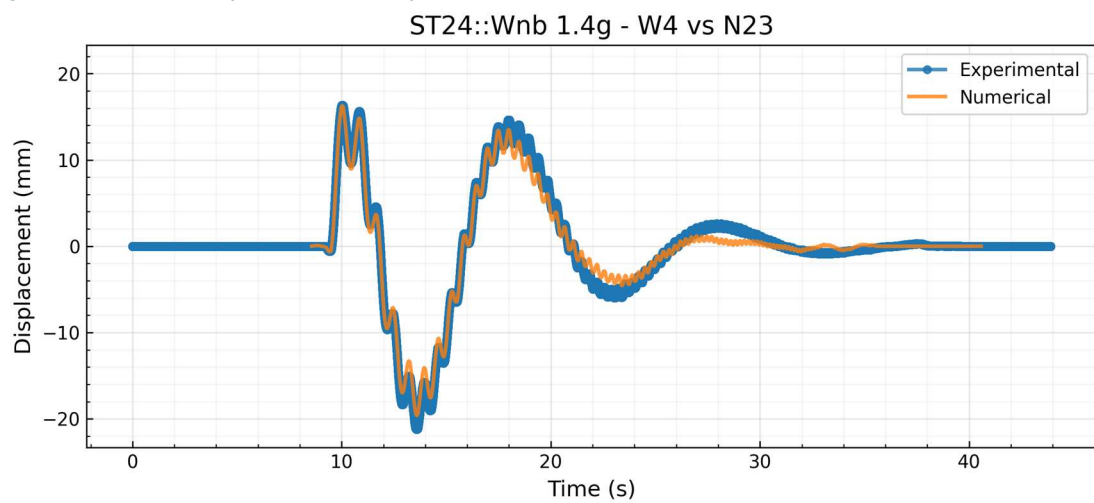


Figure 479 ST24 - Displacement comparison W4 vs N23

6.27 ST26::WNB0.2G (2) RESULTS

The result for draw-wires and accelerometers for ST26::WNB0.2g (2) are presented here.

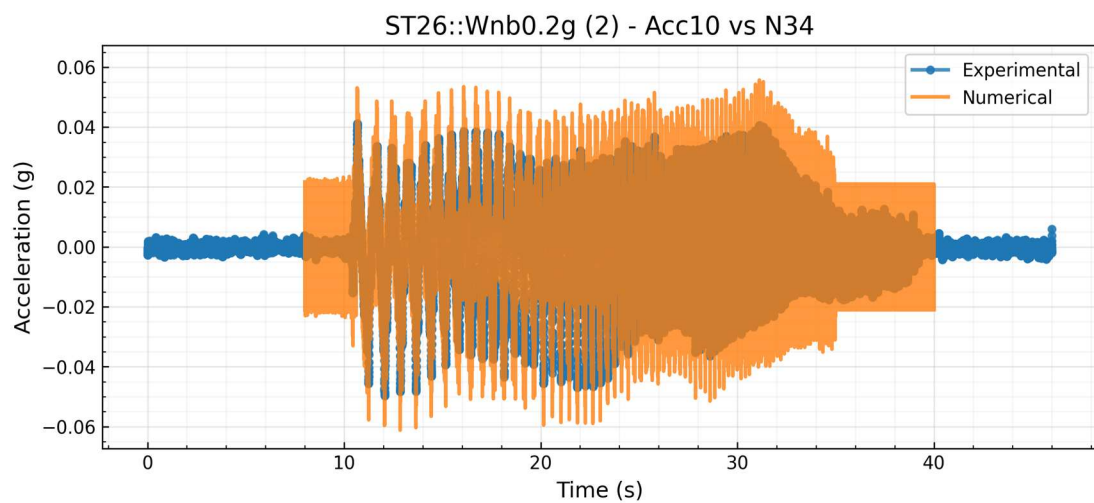


Figure 480 ST26 - Acceleration comparison Acc10 vs N34

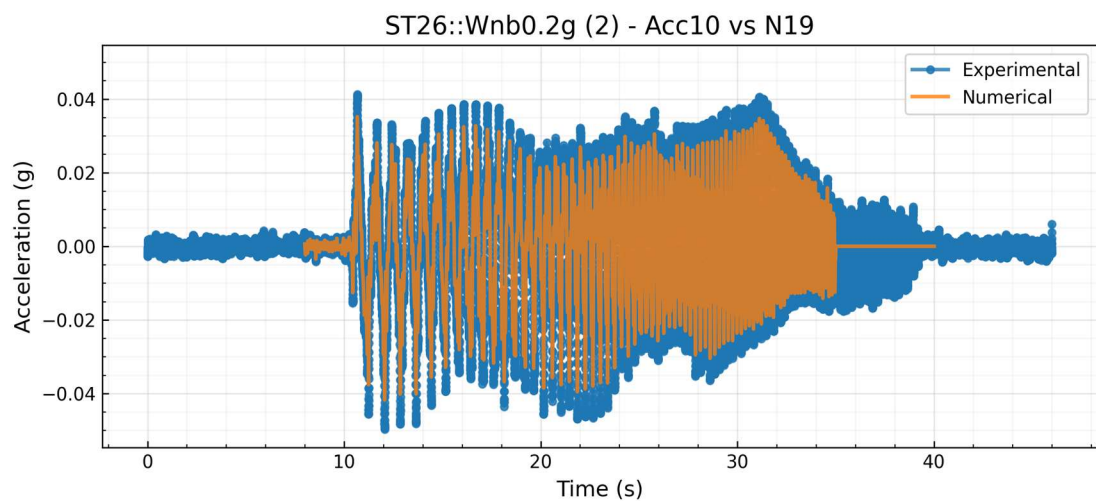


Figure 481 ST26 - Acceleration comparison Acc10 vs N19

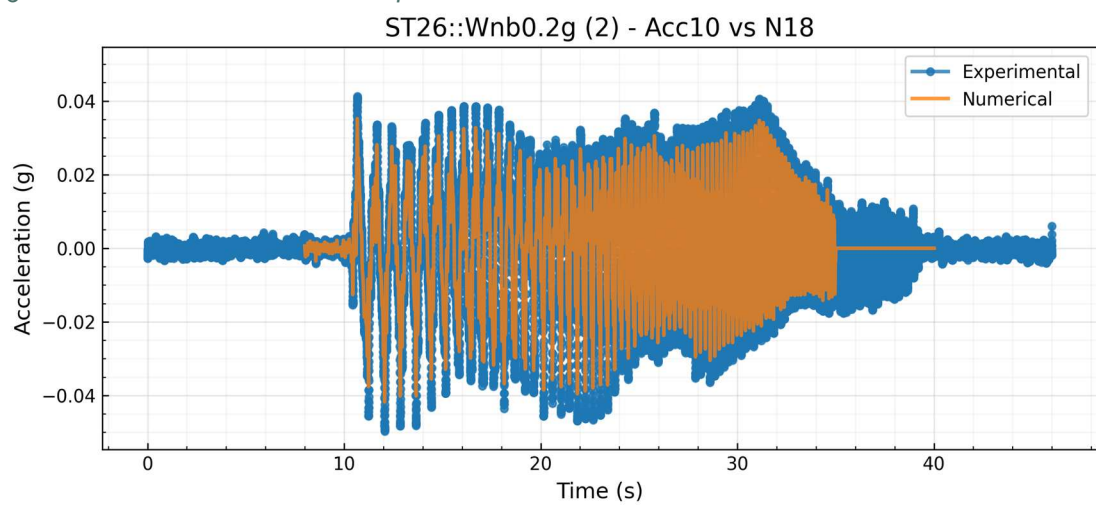


Figure 482 ST26 - Acceleration comparison Acc10 vs N18

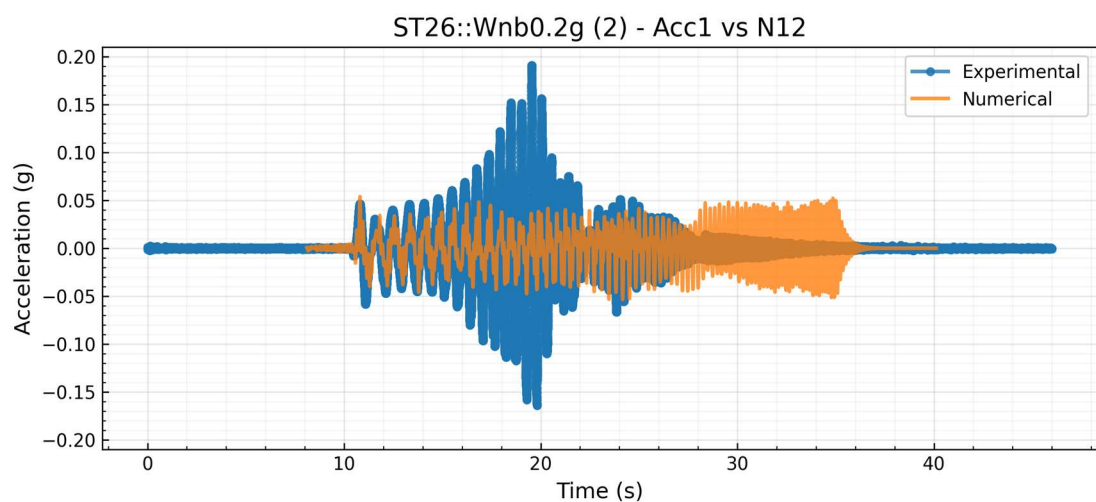


Figure 483 ST26 - Acceleration comparison Acc1 vs N12

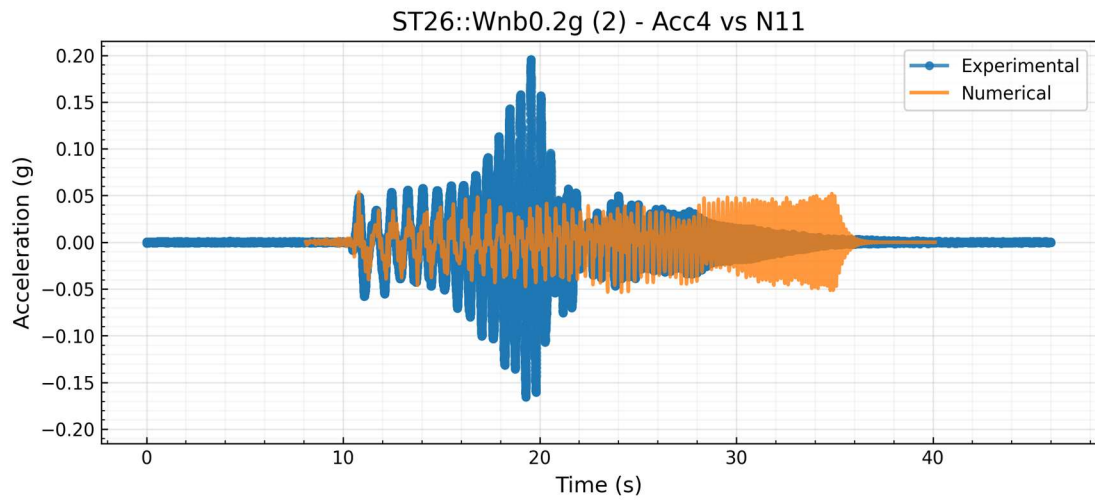


Figure 484 ST26 - Acceleration comparison Acc4 vs N11

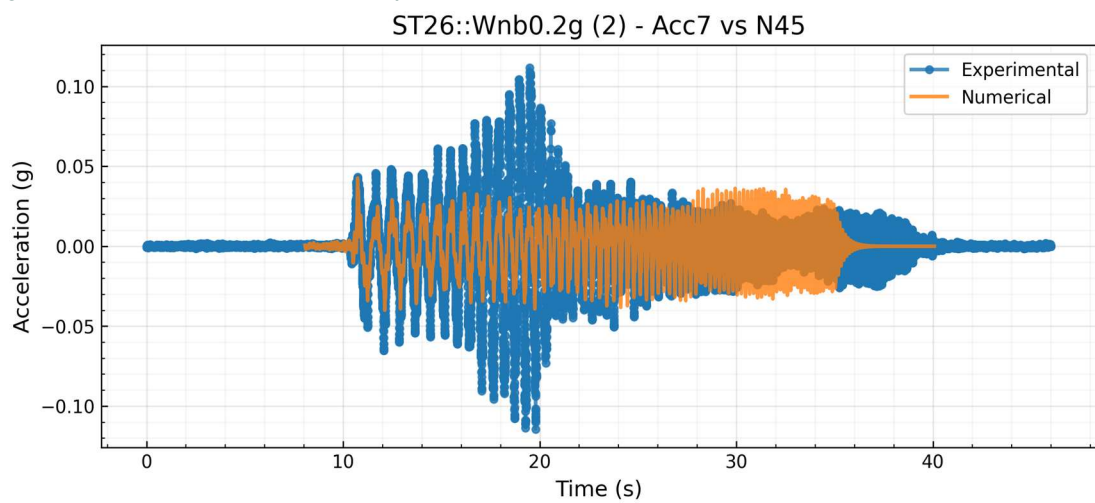


Figure 485 ST26 - Acceleration comparison Acc7 vs N45

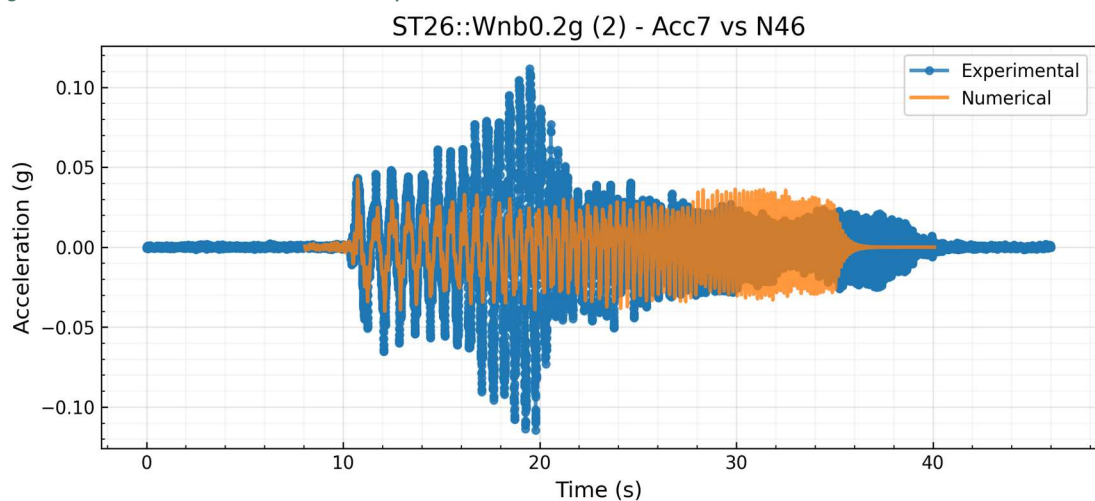


Figure 486 ST26 - Acceleration comparison Acc7 vs N46

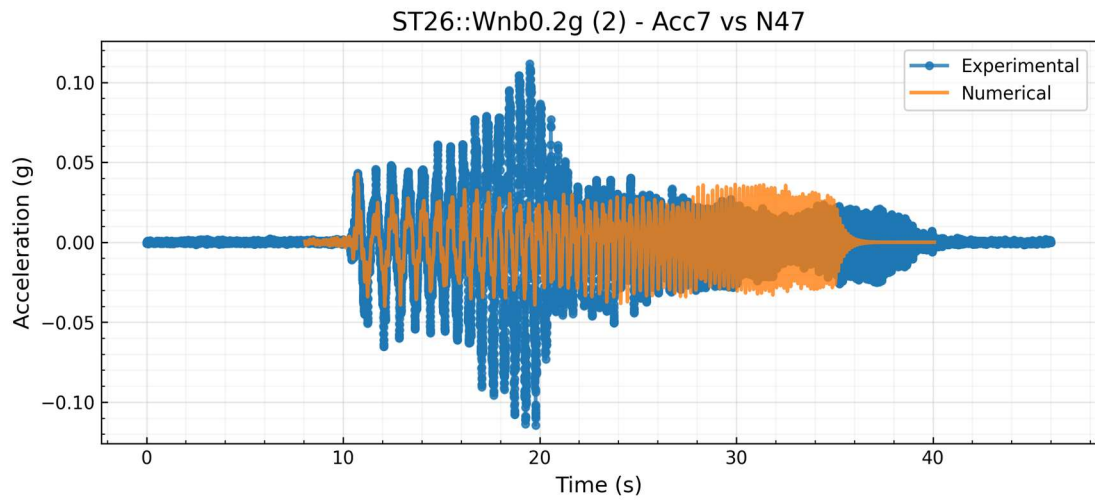


Figure 487 ST26 - Acceleration comparison Acc7 vs N47

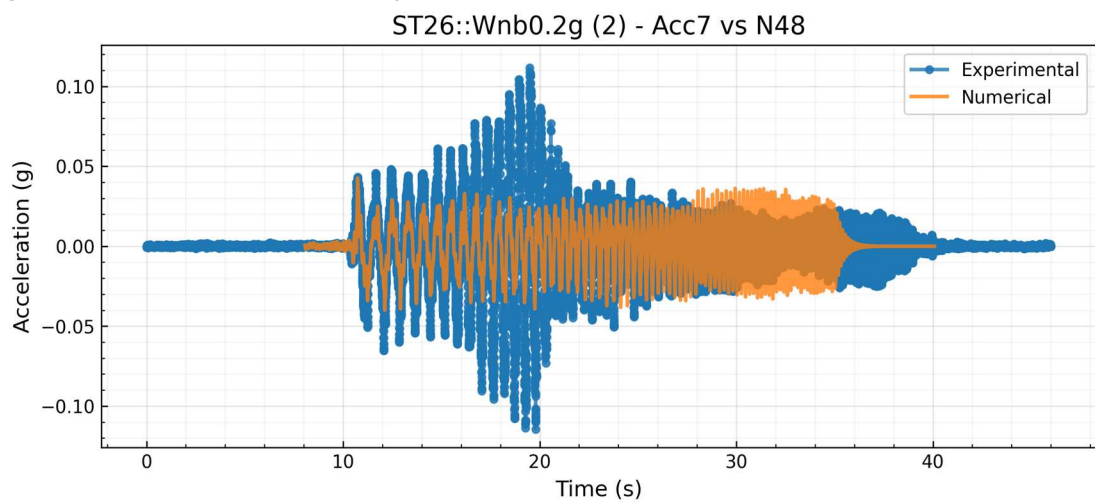


Figure 488 ST26 - Acceleration comparison Acc7 vs N48

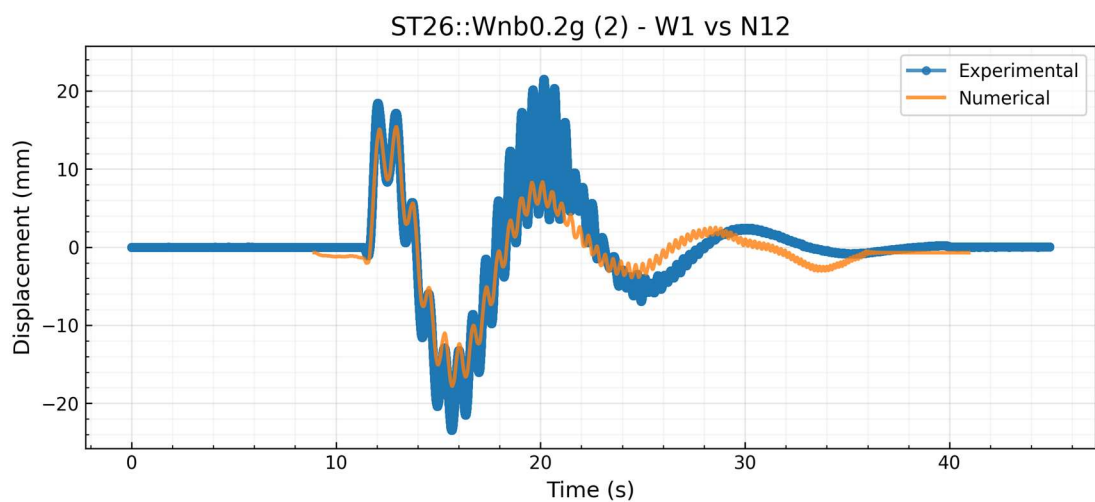


Figure 489 ST26 - Displacement comparison W1 vs N12

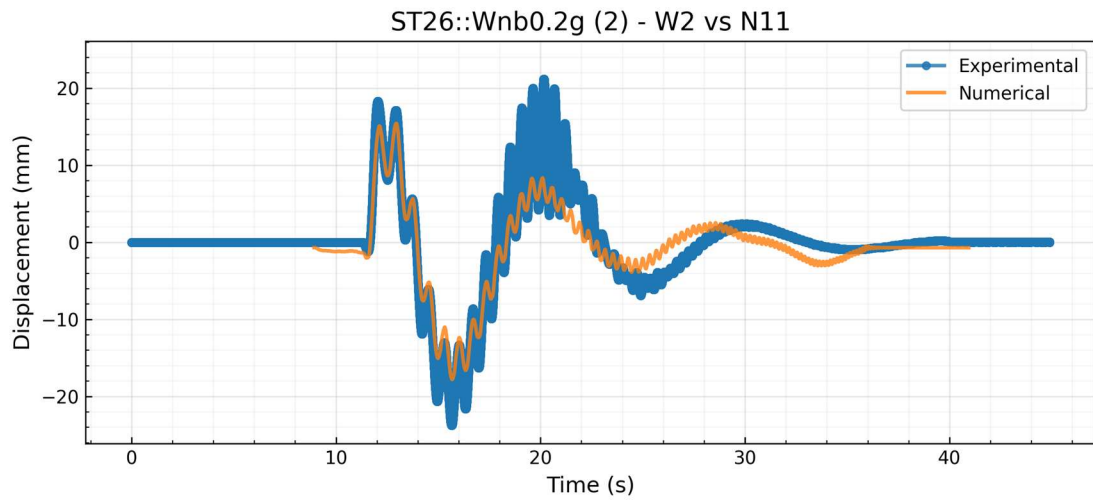


Figure 490 ST26 - Displacement comparison W2 vs N11

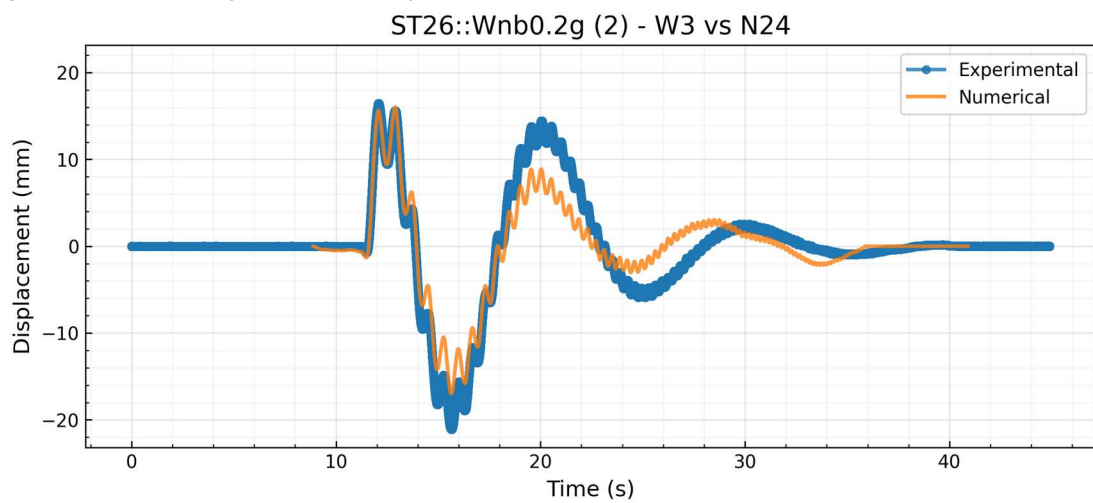


Figure 491 ST26 - Displacement comparison W3 vs N24

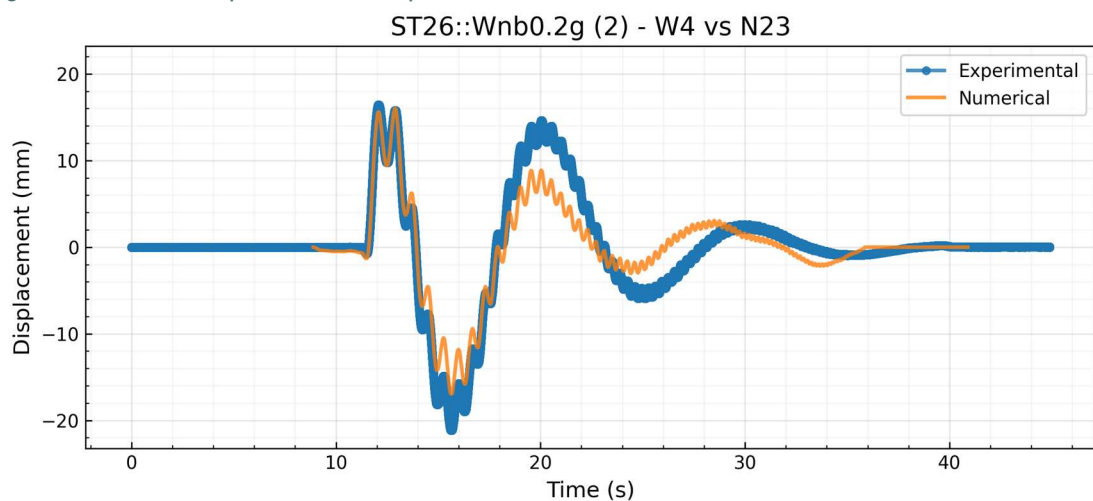


Figure 492 ST26 - Displacement comparison W4 vs N23

6.28 ST28::WNA0.2G RESULTS

The result for draw-wires and accelerometers for ST28::WNA0.2g are presented here.

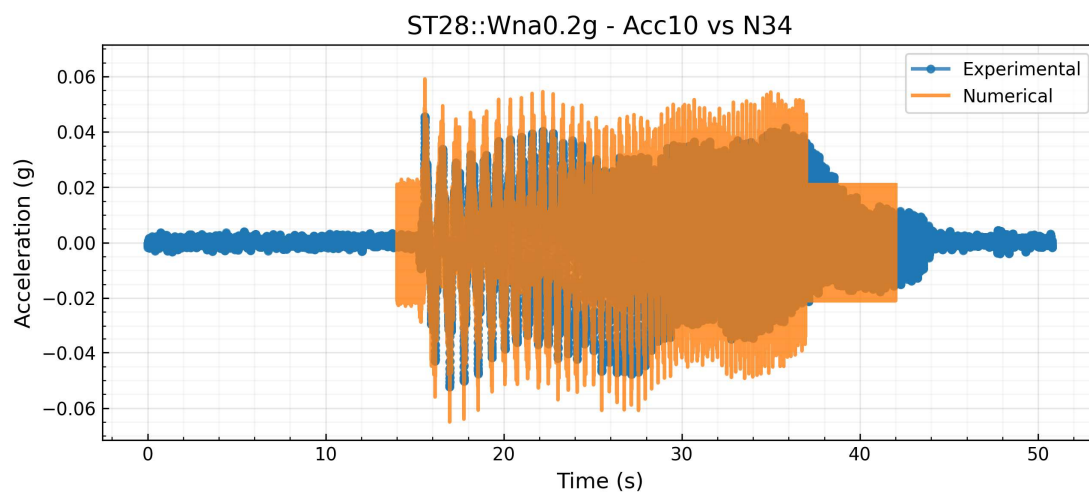


Figure 493 ST28 - Acceleration comparison Acc10 vs N34

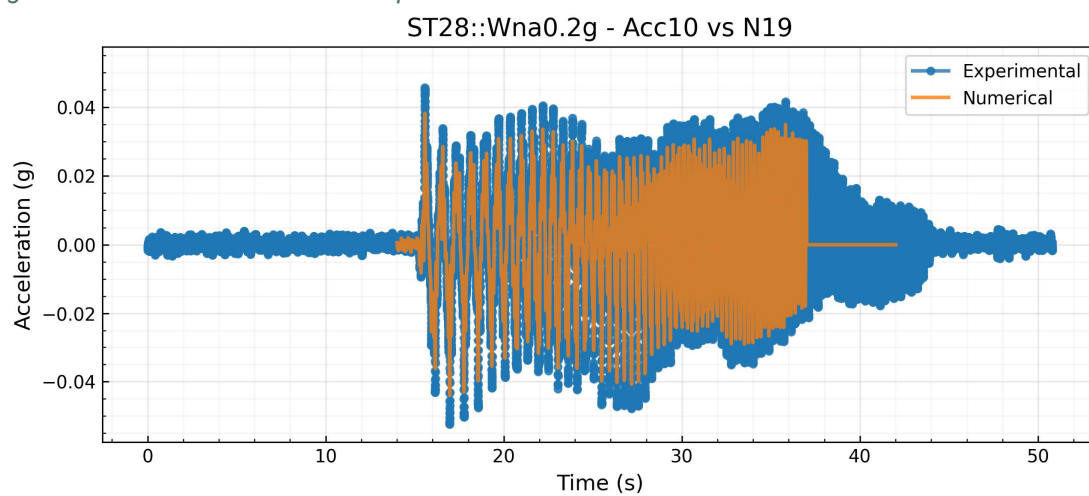


Figure 494 ST28 - Acceleration comparison Acc10 vs N19

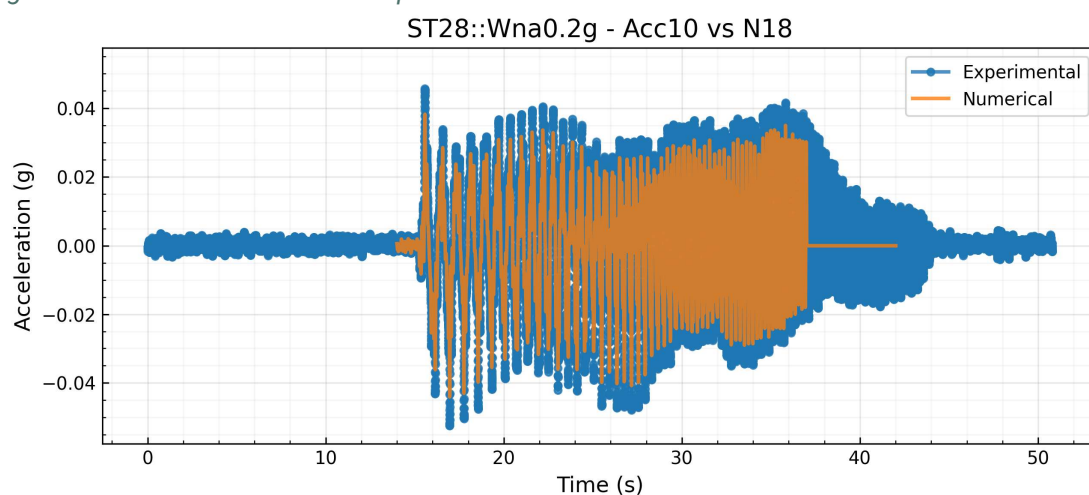


Figure 495 ST28 - Acceleration comparison Acc10 vs N18

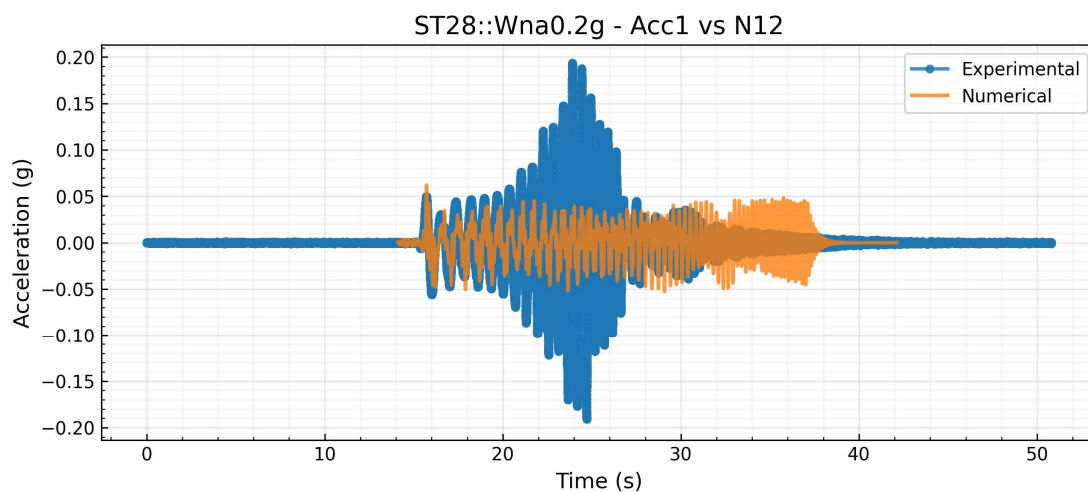


Figure 496 ST28 - Acceleration comparison Acc1 vs N12

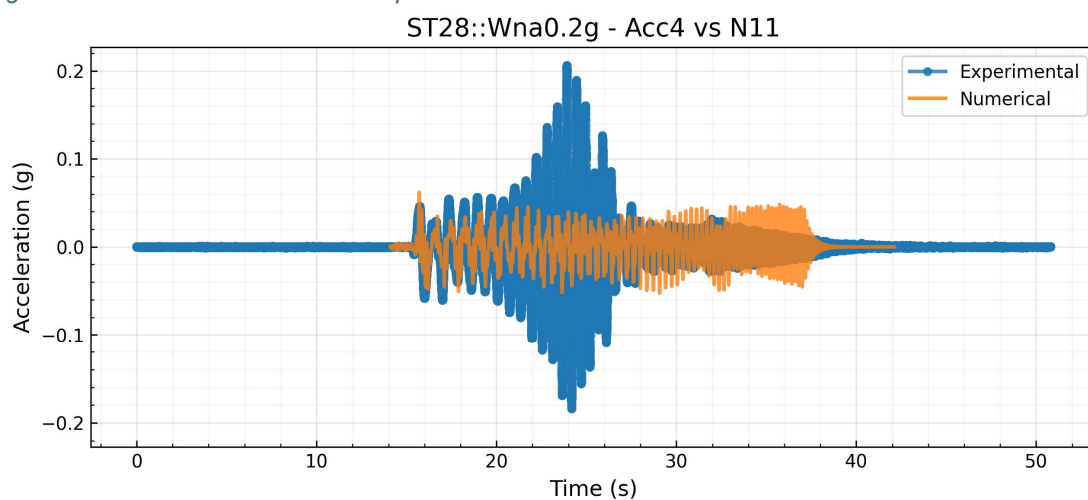


Figure 497 ST28 - Acceleration comparison Acc4 vs N11

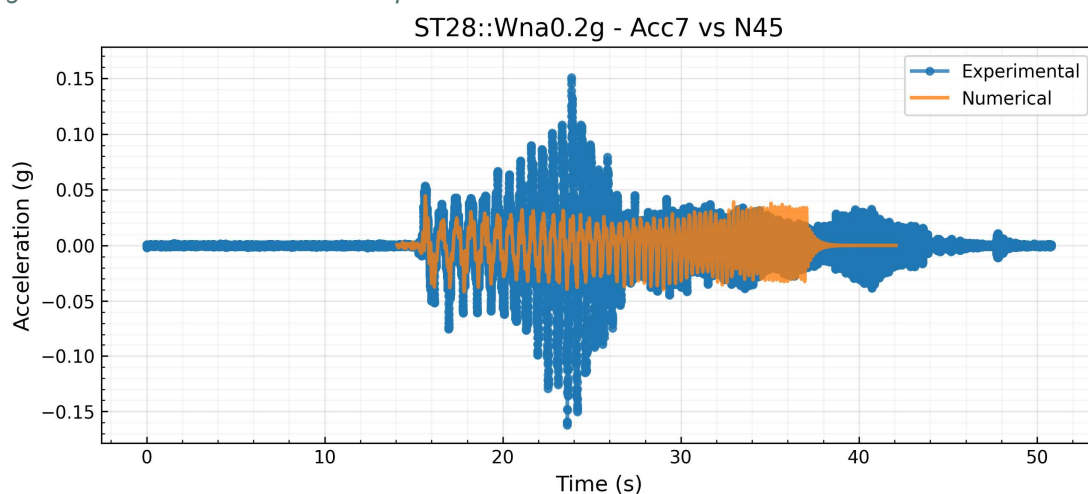


Figure 498 ST28 - Acceleration comparison Acc7 vs N45

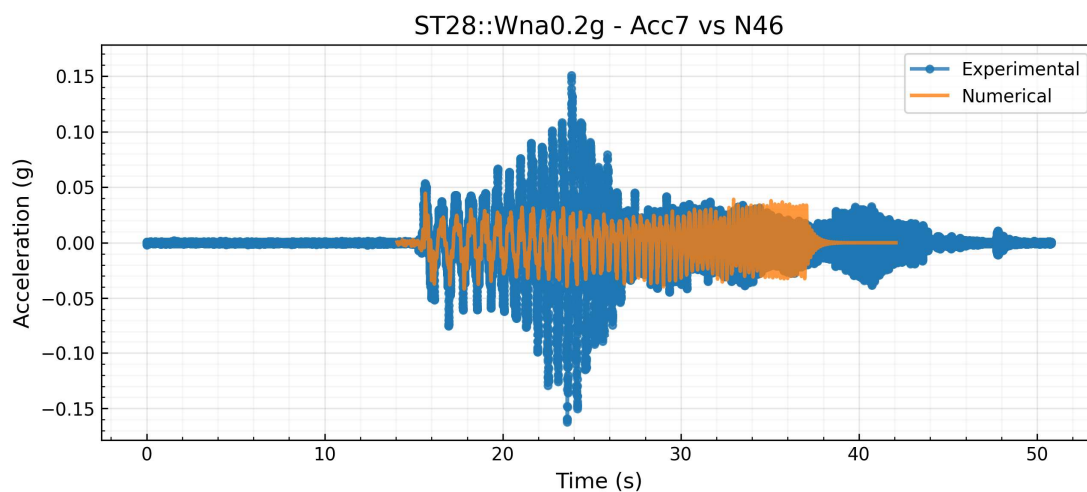


Figure 499 ST28 - Acceleration comparison Acc7 vs N46

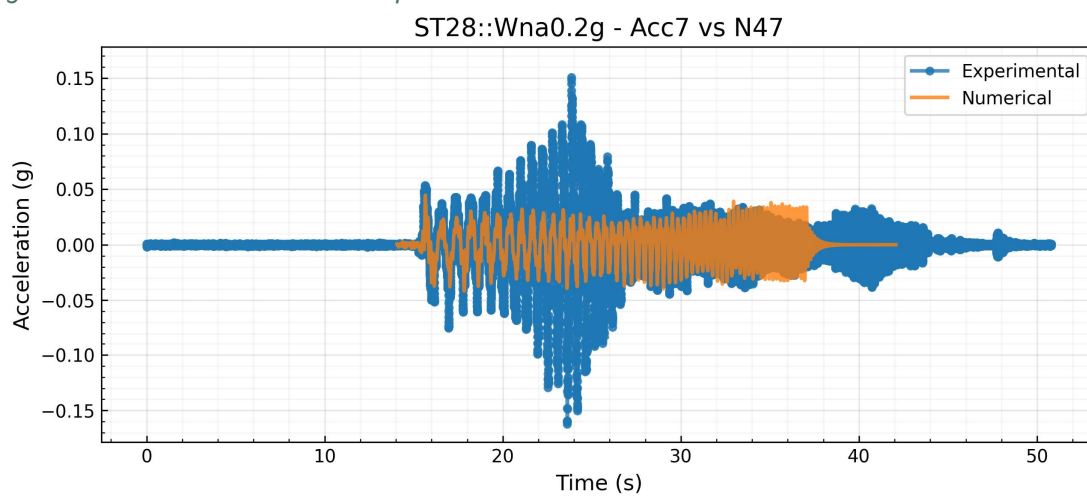


Figure 500 ST28 - Acceleration comparison Acc7 vs N47

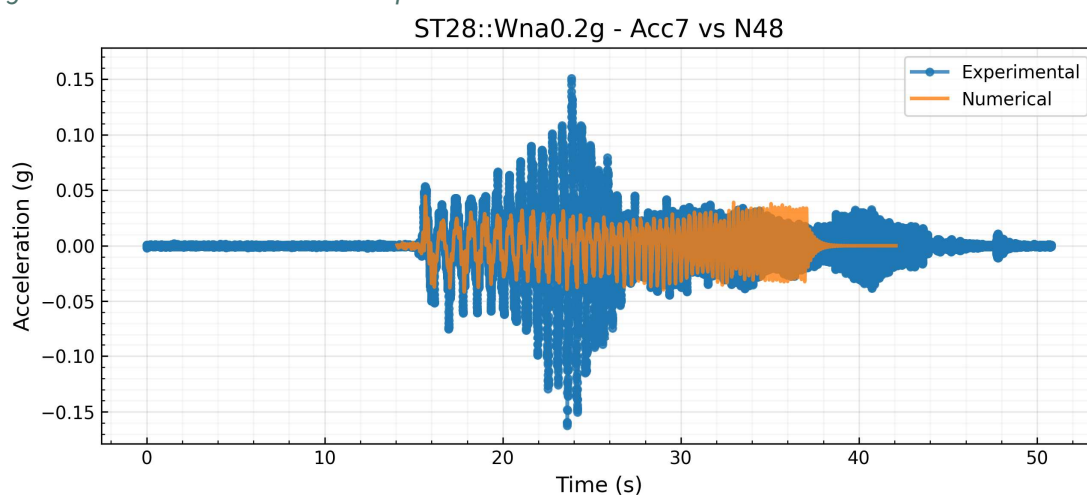


Figure 501 ST28 - Acceleration comparison Acc7 vs N48

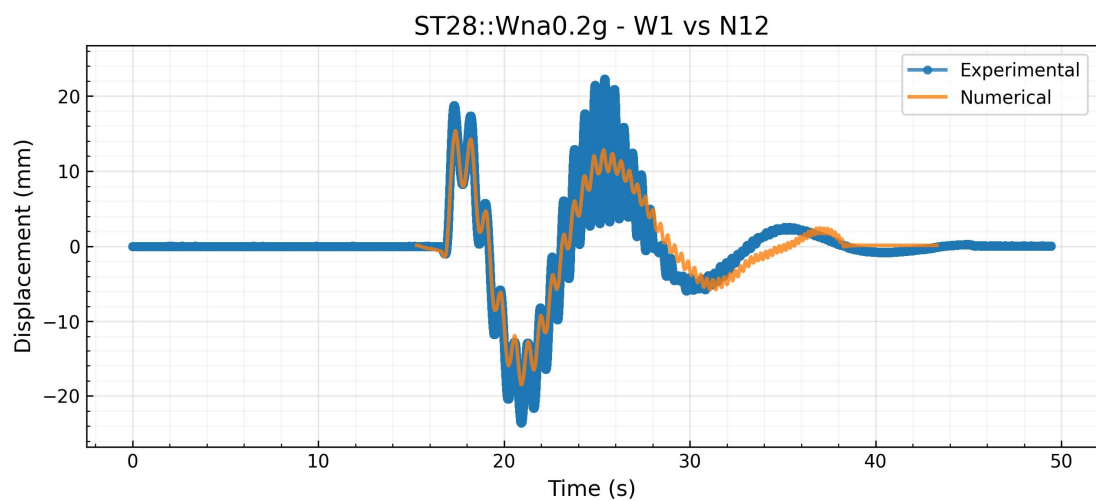


Figure 502 ST28 - Displacement comparison W1 vs N12

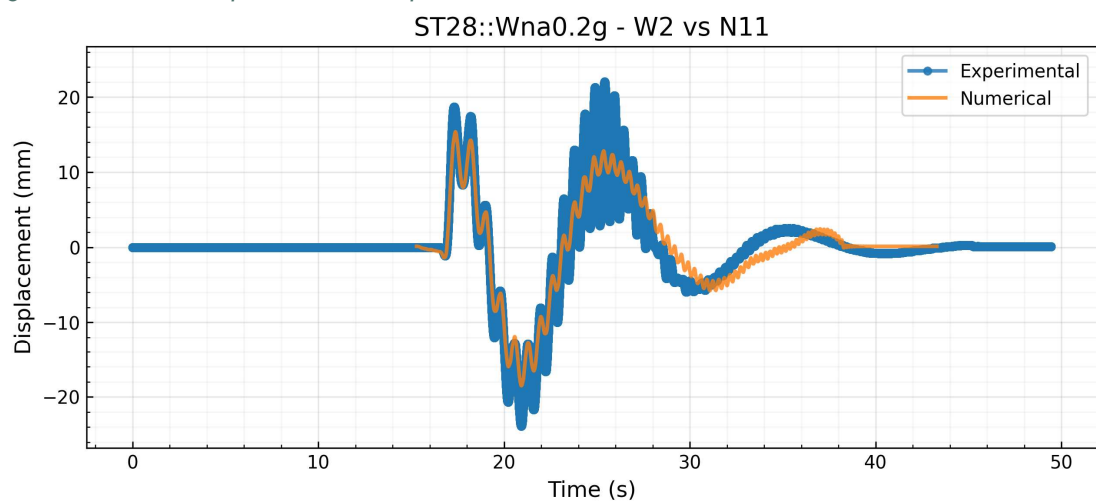


Figure 503 ST28 - Displacement comparison W2 vs N11

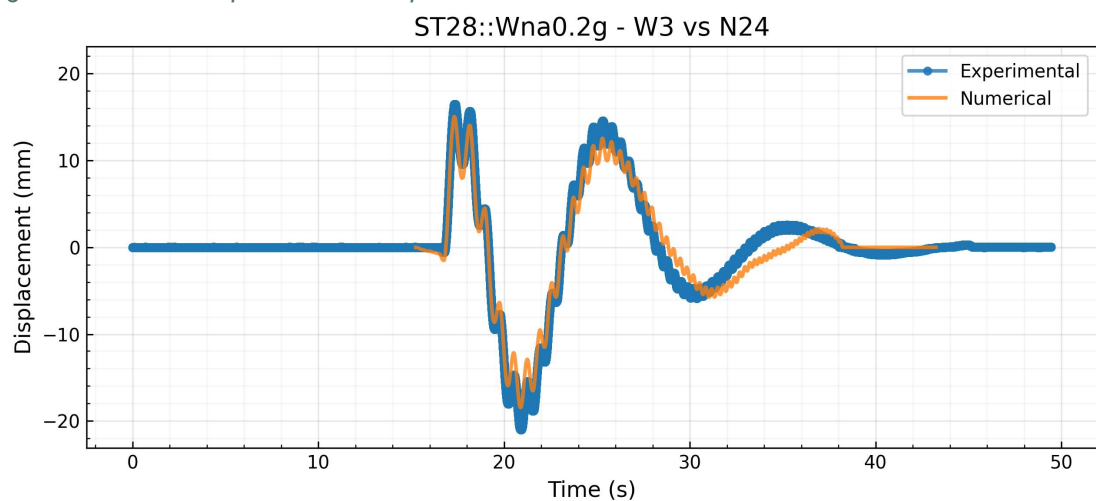


Figure 504 ST28 - Displacement comparison W3 vs N24

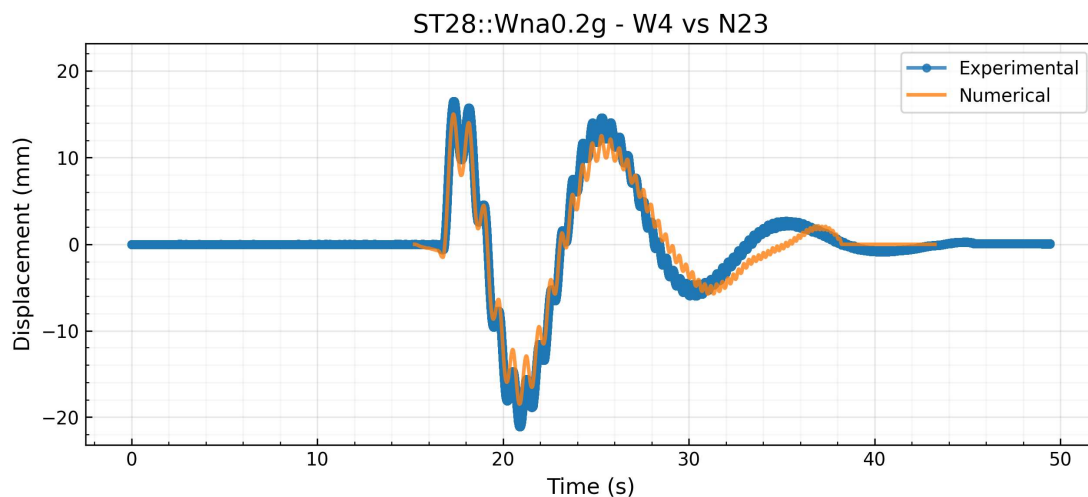


Figure 505 ST28 - Displacement comparison W4 vs N23

7 CONCLUSION

This chapter presents a comprehensive quantitative assessment of the structural performance differences observed among four distinct approaches examined in this research.

The pushover analysis results reveal significant differences in structural capacity and behavioral characteristics between the as-built and renovated configurations. The as-built specimen (Phase A) demonstrated a base shear capacity of approximately 50 kN at around 1% drift ratio (around 12 mm relative displacement). The initial tangent stiffness measured approximately 6 kN/mm (6,000 kN/m) in the elastic range. The base shear capacity was accurately predicted by both ANSYS Explicit Dynamics and ReplicaXLite simulations prior to experimental testing, validating the modeling approach for Phase A.

Following renovation (Phase B), the pushover analysis revealed transformative changes in both capacity and behavioral characteristics. The maximum lateral load capacity increased to approximately 67 kN, representing an overall 37% enhancement in base shear resistance (at different drift levels). More significantly, this capacity was achieved at 2.86% drift ratio (35 mm relative displacement)—nearly three times the relative displacement of the as-built configuration. Further, according to pushover analyses, the structure may continue to exhibit strain-hardening behavior without any detrimental strength degradation. This substantial improvement in ductility and deformation capacity represents perhaps the most critical performance enhancement, achieved through the integrated renovation strategy, despite the increased greenery mass (it resulted in around 2 mm ‘initial residual drift’ due to previous damages).

The initial tangent stiffness of the renovated structure measured approximately 2.5 kN/mm (2,500 kN/m), representing a 58% reduction compared to the as-built configuration. This stiffness reduction, rather than being detrimental, reflects the intentional design philosophy of the renovation approach: the PUFJ flexible joints introduce controlled flexibility that prevents brittle failure mechanisms, reduces stress concentrations at critical frame-infill interfaces, and enables progressive mobilization of multiple energy-dissipation mechanisms throughout the loading history. Herein, it should be noted that if the “initial residual drift is removed, then the initial tangent stiffness is higher).

The ReplicaXLite/OpenSeesPy platform demonstrated robust predictive capability across both configurations Phase A and Phase B results. All numerical predictions were satisfactorily accurate, validating the modeling approach for advanced digital twin applications with demanding, multiple excitation time histories, damage path dependent, and option of model updating among different construction-renovation stages.

The modified four-strut infill model proved particularly effective in capturing satisfactorily both in-plane and out-of-plane response (in-plane displacement and out-of-plane acceleration). The fiber-section beam-column formulation successfully captured progressive plasticity development and stiffness degradation in frame members.

The comprehensive validation against extensive shake table testing demonstrates that the developed modeling approach provides reliable tools for performance-based assessment and design of integrated structural-green retrofit interventions.

The open-source modeling platform ReplicaX Lite (Vanian & Rousakis, 2025b) provided herein, enables practitioners to apply these validated approaches to diverse retrofit projects, supporting evidence-based decision-making and performance-based design. The FRESCO database (Vanian & Rousakis, 2025) further extends the resource base for calibration and validation across varied structural configurations and strengthening systems.

Future research extending these foundations to multi-story buildings, bidirectional seismic excitation, soil-structure interaction, long-term durability, and fully integrated multi-physics performance assessment will further advance the state of knowledge and practice for vertical forest systems. The ultimate goal and vision of GREENERGY is to favor widespread implementation of resilient, sustainable, and nature-integrated urban buildings. This highly demanding task requires continued collaboration among structural engineers, architects, ecologists, and policymakers to translate research findings into practical design guidelines, code provisions, and built demonstrations that incorporate advanced structural health monitoring approaches.

REFERENCES

- Akhoundi, F., Silva, L. M., Vasconcelos, G., & Lourenço, P. (2023). Out-of-plane strengthening of masonry infills using Textile Reinforced Mortar (TRM) technique. *International Journal of Architectural Heritage*, 17(2), 310–325.
- Bouarroudj, M. A., & Boudaoud, Z. (2022). Comparison Between Numerical Modeling Approaches of Infilled Frames Under In-Plane Load. *Frontiers in Built Environment*, 7, 783051. <https://doi.org/10.3389/fbuil.2021.783051>
- Chrysostomou, C. Z., Gergely, P., & Abel, J. F. (2002). A SIX-STRUT MODEL FOR NONLINEAR DYNAMIC ANALYSIS OF STEEL INFILLED FRAMES. *International Journal of Structural Stability and Dynamics*, 02(03), 335–353. <https://doi.org/10.1142/S0219455402000567>
- Crisafulli, F. J., & Carr, A. J. (2007). Proposed macro-model for the analysis of infilled frame structures. *Bulletin of the New Zealand Society for Earthquake Engineering*, 40(2), 69–77. <https://doi.org/10.5459/bnzsee.40.2.69-77>
- Di Trapani, F., Shing, P. B., & Cavaleri, L. (2018). Macroelement Model for In-Plane and Out-of-Plane Responses of Masonry Infills in Frame Structures. *Journal of Structural Engineering*, 144(2), 04017198. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0001926](https://doi.org/10.1061/(ASCE)ST.1943-541X.0001926)
- Donà, M., Tecchio, G., Domenicale, L., Saler, E., Minotto, M., & Da Porto, F. (2017). DIRECTIONAL EFFECTS ON COMBINED IN-PLANE AND OUT OF PLANE SEISMIC BEHAVIOR OF MASONRY INFILLS. *Proceedings of the 6th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2015)*, 3332–3351. <https://doi.org/10.7712/120117.5649.18570>
- El-Dakhakhni, W. W., Elgaaly, M., & Hamid, A. A. (2003). Three-Strut Model for Concrete Masonry-Infilled Steel Frames. *Journal of Structural Engineering*, 129(2), 177–185. [https://doi.org/10.1061/\(ASCE\)0733-9445\(2003\)129:2\(177\)](https://doi.org/10.1061/(ASCE)0733-9445(2003)129:2(177))
- FEMA 356, F. E. (2000). Prestandard and commentary for the seismic rehabilitation of buildings. *Federal Emergency Management Agency: Washington, DC, USA*.

- Furtado, A., Rodrigues, H., & Arêde, A. (2015). Modelling of masonry infill walls participation in the seismic behaviour of RC buildings using OpenSees. *International Journal of Advanced Structural Engineering*, 7(2), 117–127. <https://doi.org/10.1007/s40091-015-0086-5>
- Gesualdi, G., Viggiani, L. R. S., & Cardone, D. (2020). Seismic performance of RC frame buildings accounting for the out-of-plane behavior of masonry infills. *Bulletin of Earthquake Engineering*, 18(11), 5343–5381. <https://doi.org/10.1007/s10518-020-00904-1>
- Holmes, M. (1961). STEEL FRAMES WITH BRICKWORK AND CONCRETE INFILLING. *Proceedings of the Institution of Civil Engineers*, 19(4), 473–478. <https://doi.org/10.1680/iicep.1961.11305>
- Kadysiewski, S., & Mosalam, K. M. (2009). *Modeling of unreinforced masonry infill walls considering in-plane and out-of-plane interaction* (Vol. 70). Pacific Earthquake Engineering Research Center Berkeley.
- Koutas, L. N., & Bournas, D. A. (2019). Out-of-Plane Strengthening of Masonry-Infilled RC Frames with Textile-Reinforced Mortar Jackets. *Journal of Composites for Construction*, 23(1), 04018079. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000911](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000911)
- Mainstone, R. J. (1971). On the stiffness and strength of infilled frames. *Proc Inst Civil Eng*, 49, 57.
- Mainstone, R. J. (1974). *Supplementary note on the stiffness and strength of infilled frames* (No. CP 13/74). Building Research Establishment.
- Mazza, F., & Donnici, A. (2021). In-plane and out-of-plane seismic damage of masonry infills in existing r.c. structures: The case study of De Gasperi-Battaglia school in Norcia. *Bulletin of Earthquake Engineering*, 19(1), 345–376. <https://doi.org/10.1007/s10518-020-00981-2>
- McKenna, F. (2011). OpenSees: A framework for earthquake engineering simulation. *Computing in Science & Engineering*, 13(4), 58–66.
- Mosalam, K. M., & Günay, S. (2015). Progressive Collapse Analysis of Reinforced Concrete Frames with Unreinforced Masonry Infill Walls considering In-Plane/Out-of-Plane Interaction. *Earthquake Spectra*, 31(2), 921–943. <https://doi.org/10.1193/062113EQS165M>
- Pradhan, B., & Cavaleri, L. (2020). IP-OOP interaction in URM infilled frame structures: A new macro-modelling proposal. *Engineering Structures*, 224, 111211. <https://doi.org/10.1016/j.engstruct.2020.111211>
- Rodrigues, H., Varum, H., & Costa, A. (2010). Simplified Macro-Model for Infill Masonry Panels. *Journal of Earthquake Engineering*, 14(3), 390–416. <https://doi.org/10.1080/13632460903086044>
- Rostamkalae, S., Peloso, S., & Brunesi, E. (2023). Macro-Modelling of IP-OoP Interaction in Unreinforced Solid Masonry Infills under Earthquake-Induced Actions: A Review. *Buildings*, 13(9), 2326. <https://doi.org/10.3390/buildings13092326>
- Rousakis, T., Voutetaki, M., Kellis, S., Zapris, A., Lappa, M., Xynopoulos, I., Sapidis, G., Papadopoulos, N., Karampini, M., Mallinis, G., Stefanidou, M., & Theodoridou, I. (2024). *Designs and photos of detailing and instrumentation of constructed as-built 3d structure. Greenery-Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas (H.F.R.I. Project Number 015376). Deliverable D2.1.* Democritus University of Thrace, Xanthi.
- Rousakis, T., Voutetaki, M., Vanian, V., Fanaradelli, T., & Zapris, A. (2024). *Literature review on VF buildings' modeling for combined renovation covering structural, energy, forestry and habitant comfort aspects. Greenery-Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas (H.F.R.I. Project Number 015376). Deliverable D3.1.* Democritus University of Thrace, Xanthi.

- Smith, B. S. (1962). Lateral Stiffness of Infilled Frames. *Journal of the Structural Division*, 88(6), 183–199. <https://doi.org/10.1061/JSDEAG.0000849>
- Theodoridou, I., Vatitsi, K., Stefanidou, M., Vanian, V., Fanaradelli, T., Macha, M., Zapris, A., Kytinou, V., Voutetaki, M., Rousakis, T., Mallinis, G., & Chalioris, C. (2025). Nature-Based Solutions for Urban Buildings—The Potential of Vertical Greenery: A Brief Review of Benefits and Challenges of Implementation. *Urban Science*, 9(10), 398. <https://doi.org/10.3390/urbansci9100398>
- Vanian, V., Akyildiz, A., Rousakis, T., & Kwiecien, A. (2024). Dynamic Modeling and Analysis of RC Frames Filled with URM Panels Protected with Flexible Connectors. *Proceedings of the 18th World Conference on Earthquake Engineering, Milan, Italy*, 30.
- Vanian, V., Fanaradelli, T., & Rousakis, T. (2025). A Comprehensive Review of Vertical Forest Buildings: Integrating Structural, Energy, Forestry, and Occupant Comfort Aspects in Renovation Modeling. *Fibers*, 13(8), 101. <https://doi.org/10.3390/fib13080101>
- Vanian, V., & Rousakis, T. (2025a). FRESCO: An Open Database for Fiber and Polymer Strengthening of Infilled RC Frame Systems. *Fibers*, 13(11), 152. <https://doi.org/10.3390/fib13110152>
- Vanian, V., & Rousakis, T. (2025b). ReplicaX Lite: A finite element toolkit for creating, analyzing and monitoring 3D structural models. In *GitHub Repository* [Computer software]. GitHub. <https://github.com/Vachan-Vanian/ReplicaX Lite>
- Vanian, V., Rousakis, T., Fanaradelli, T., Voutetaki, M., Macha, M., Zapris, A., Theodoridou, I., Stefanidou, M., Vatitsi, K., Mallinis, G., Kytinou, V., & Chalioris, C. (2025). Performance-Based Damage Quantification and Hazard Intensity Measures for Vertical Forest Systems on RC Buildings. *Buildings*, 15(5), 769. <https://doi.org/10.3390/buildings15050769>
- Yekrangnia, M., & Mohammadi, M. (2017). A new strut model for solid masonry infills in steel frames. *Engineering Structures*, 135, 222–235. <https://doi.org/10.1016/j.engstruct.2016.10.048>