DIPARTIMENTO di INGEGNERIA

LA RICERCA DENTRO UNIME

KU LEUVEN

SACERTIS INGEGNERIA

Safety evaluation of road infrastructures through unconventional dynamic monitoring and Operational Modal Analysis (OMA) methodologies

Prestressed Concrete Beams with Artificially Damaged Strands: Plan of Experimental Tests and Numerical Modeling

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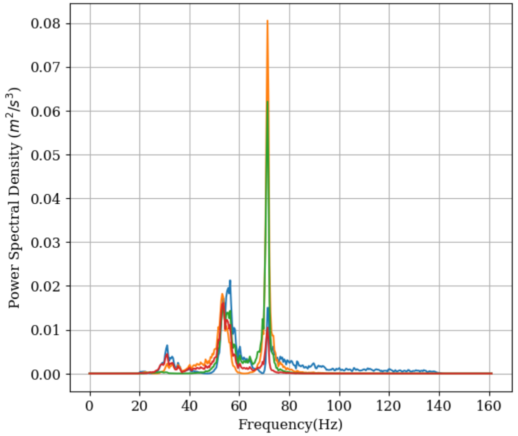
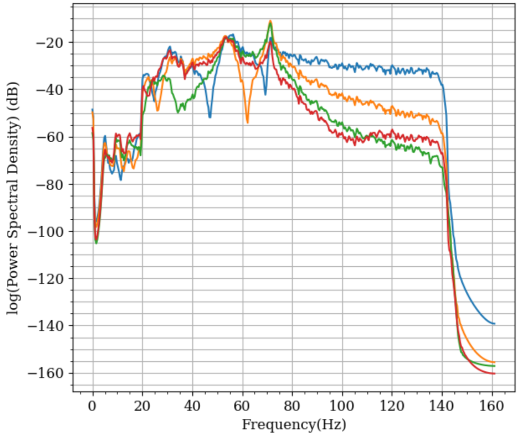
12 gennaio 2026

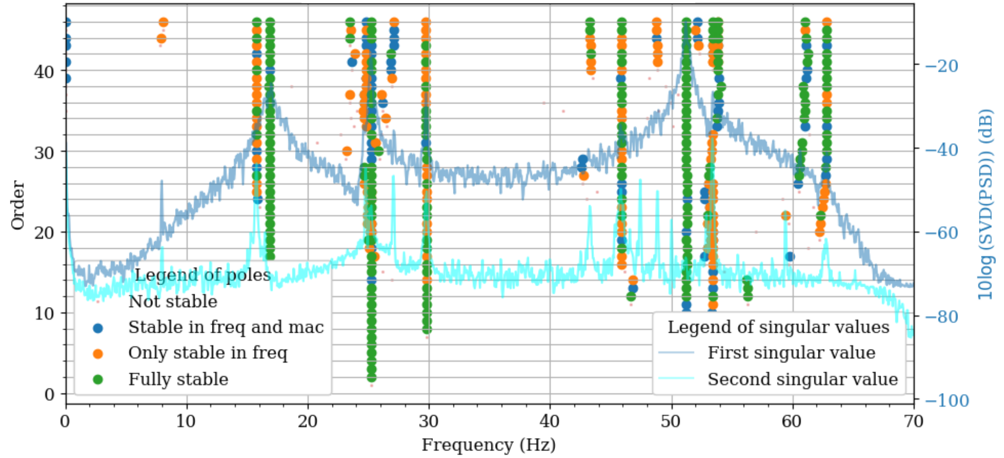
Application of OMA Techniques in Python

Application of OMA: Implementing OMA techniques like EFDD, SSI-COV, SSI-DATA, and PolyMax to analyze structural dynamics in response in a new python library (Modalyzer)

```python
print('Please upload the EFDD_func.py ...')
# files.upload()
# importlib.reload(EFDD_func)  # Reload the module
from EFDD_func import FDD_SVD_Diagram, FDD_ModeShape, FDD_Damping, MAC_Calculation

print('upload SSI_func.py ...')
# files.upload()
from SSI_func import SSI_Alg, psd_func, svd_psd, stabilization_diagram

print('upload PolyMAX_func.py ...')
# files.upload()
from PolyMAX_func import PolyMAX, independent_mode_shape

print('Please upload the ITD_func.py ...')
# files.upload()
from ITD_func import ITD_alg

from Preprocess import preprocess, results_table, choose_modes
from ModeShape import draw_mode_shapes, draw_MAC_diagram
```
✓ 0.0s

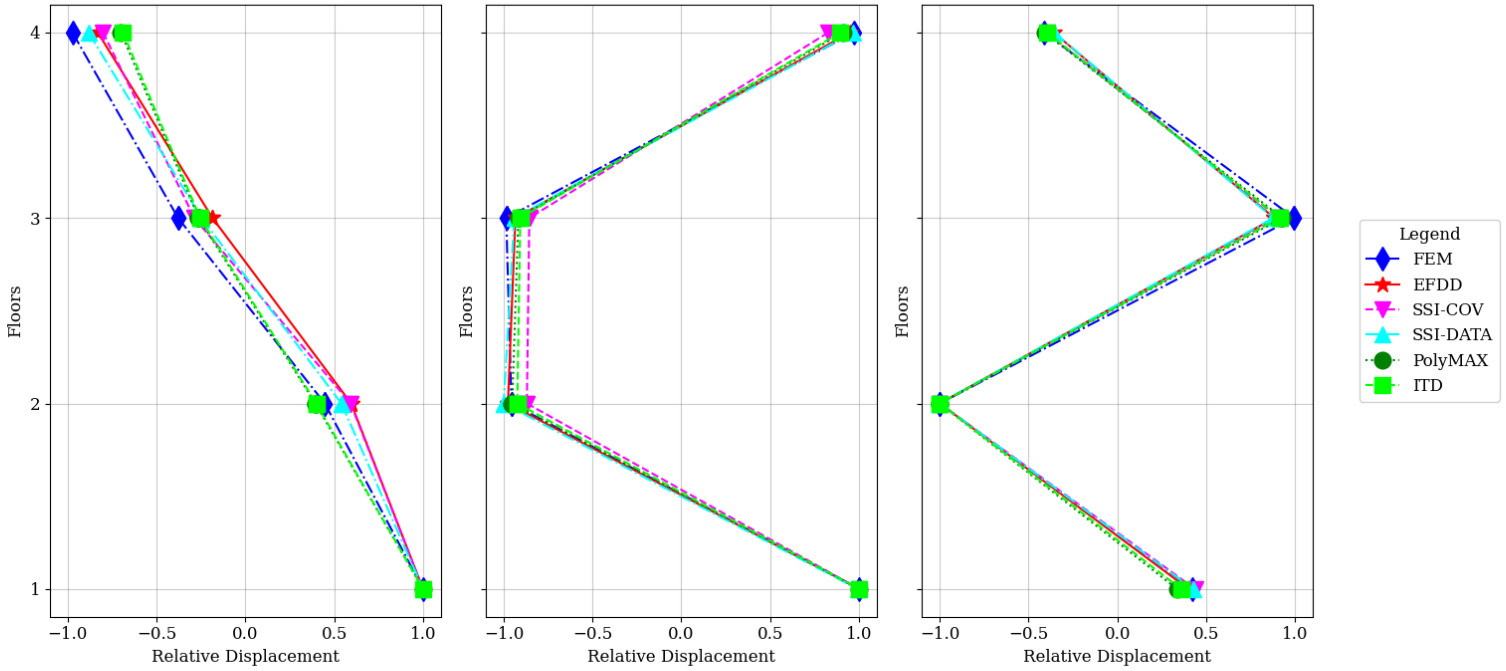


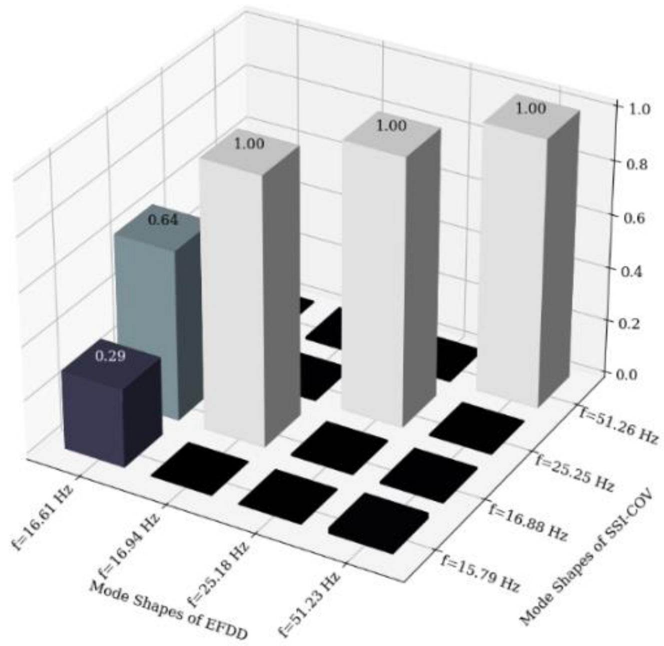


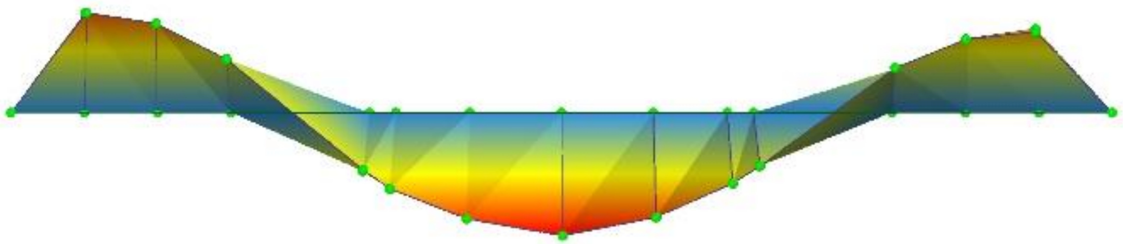


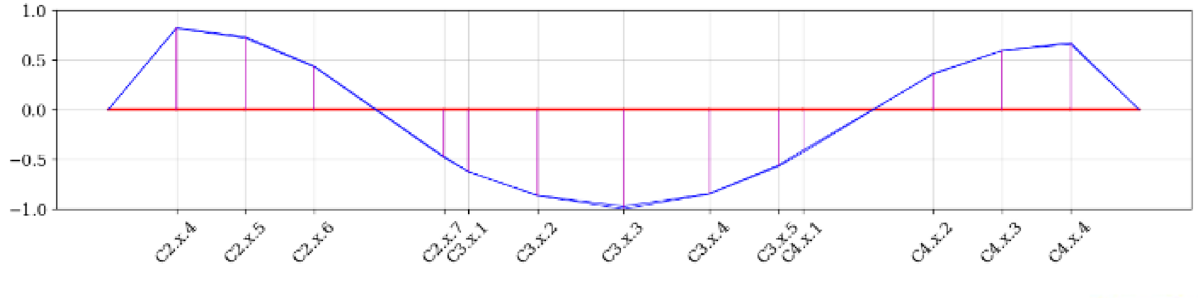
Application of OMA Techniques in Python

Application of OMA: Mode shapes and MAC matrix









Experimental campaign

1. OBJECTIVES

- Investigate structural health monitoring techniques for prestressed concrete bridge girders.
- Perform experimental testing on artificially damaged strands in a controlled lab environment.
- Use advanced sensors and acquisition units provided by SACERTIS to validate results.

"These objectives aim to advance the understanding of structural damage detection through dynamic monitoring."

2. CONSTRAINTS

Lab Constraints:

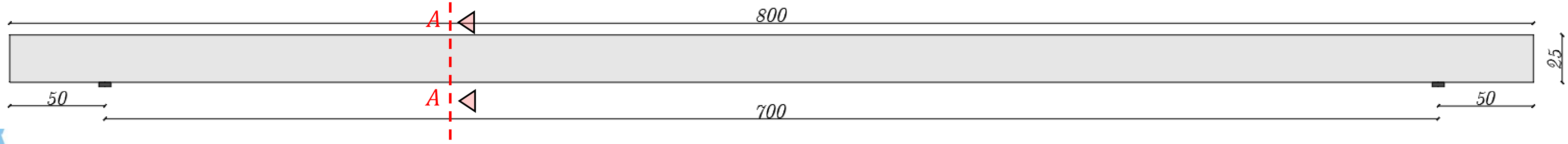
- Actuator Sizes: 250 kN, 500 kN, and 1000 kN.
- Control Modes: Displacement-controlled or force-controlled.
- Testing Area Dimensions: 9.0 m x 7.0 m, height 5.0 m.

"These constraints define the boundaries of the experimental campaign and influence the design of test setups."

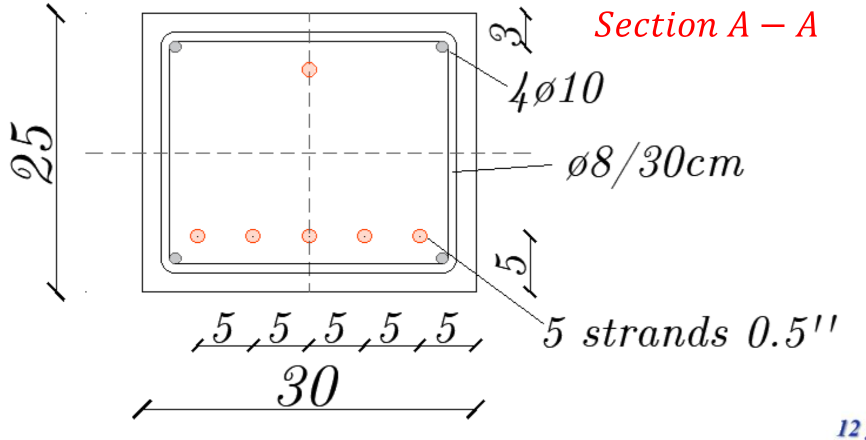
DESIGN OF PRESTRESSED CONCRETE BEAM

Cross section geometry: 30 cm x 25 cm

Length = ? ⇨ 8.0 m ⇨ 12 prototypes of 8.0 m each (96.0 m of the 100.0 m casting slot), clear span $L = 7.0\ m$



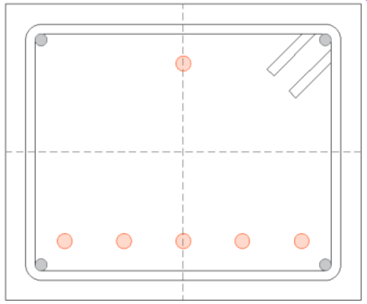
Reinforcement = ? ⇨ 5+1 prestressing strands 0.5”,
area $A_t = 93$ mm^2 each

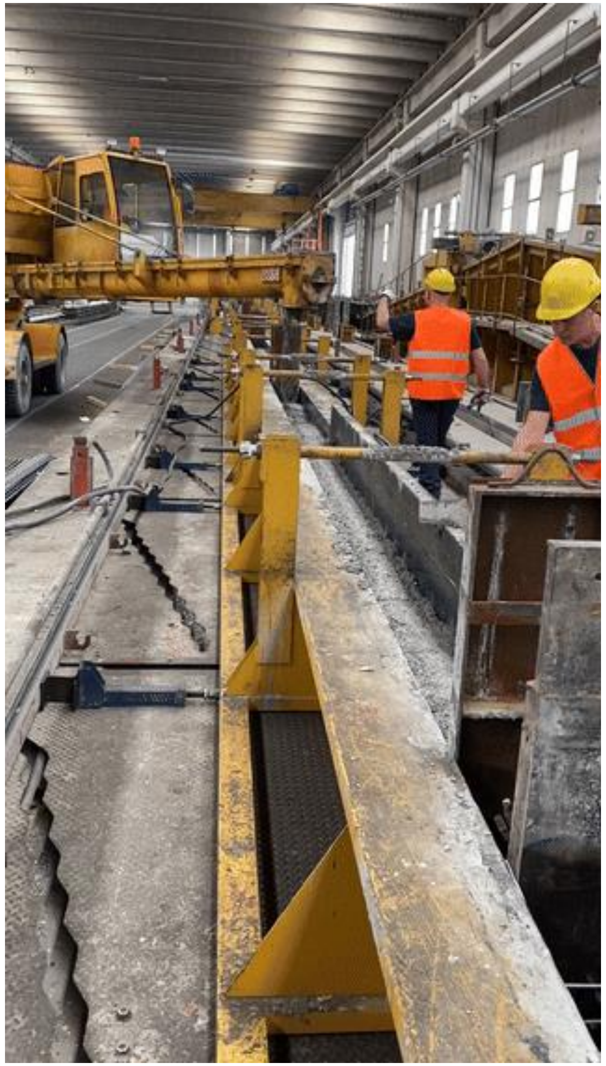


Beam Design and Manufacturer Constraints

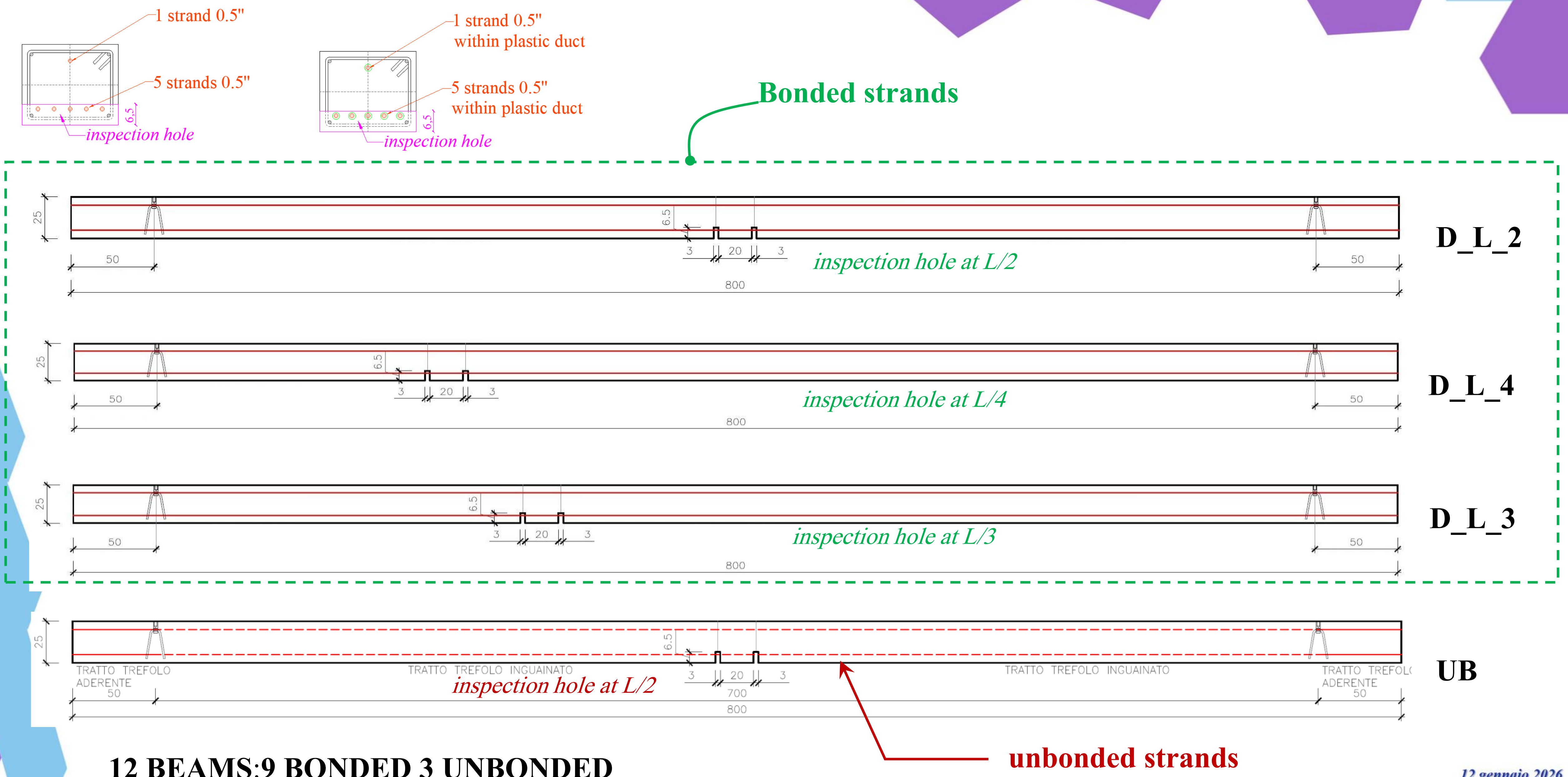
- prestressing strands spacing 5.0 cm in both vertical and horizontal direction
- minimum diameter for prestressing reinforcement ½'' ($A_t = 93\ \text{mm}^2$)
- recommended concrete class C45/55 ($R_{ck} = 55$ MPa)
- recommended size of concrete section 30 x 25 cm to exploit ongoing casting setup
- recommended length of total casting 100.0 m
- strands release: approx. 16 hours from casting, when cubic mean strength is at least 35 MPa

Casting of the specimens



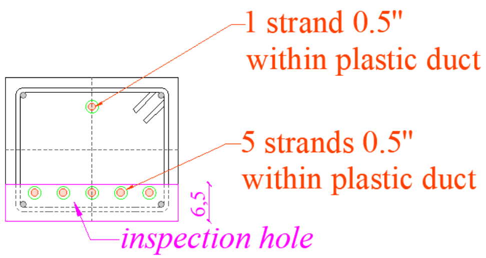


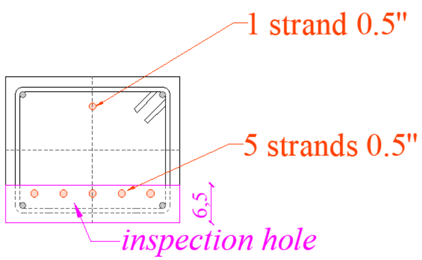
Types of specimens



12 BEAMS:9 BONDED 3 UNBONDED

Types of specimens

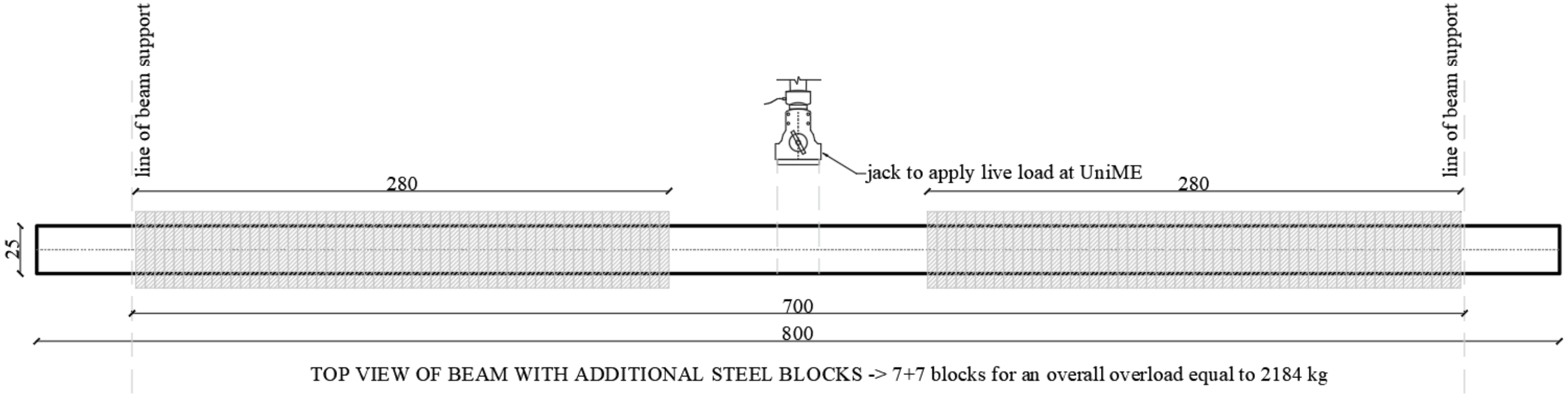




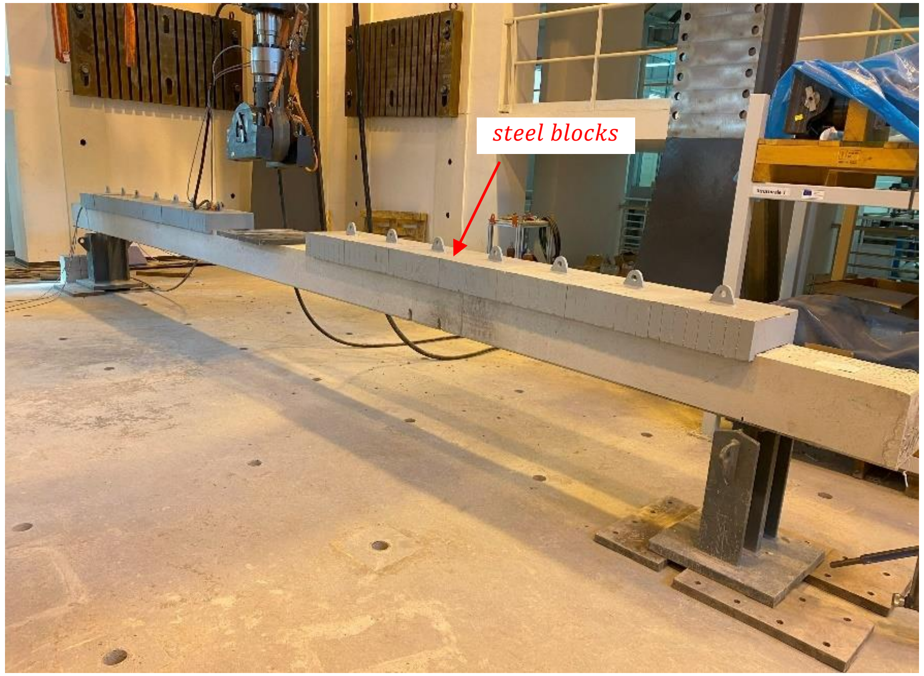
unbonded strands

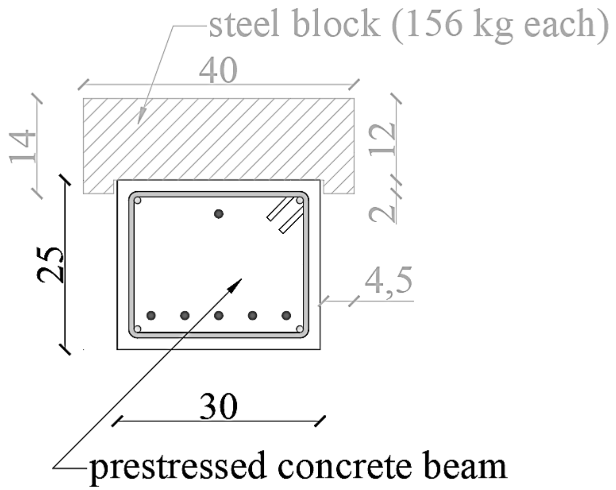
Bonded strands

OVERLOAD WITH ADDED STEEL BLOCKS ON THE BEAM

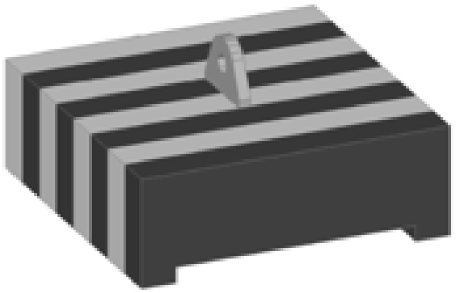


TOP VIEW OF BEAM WITH ADDITIONAL STEEL BLOCKS -> 7+7 blocks for an overall overload equal to 2184 kg

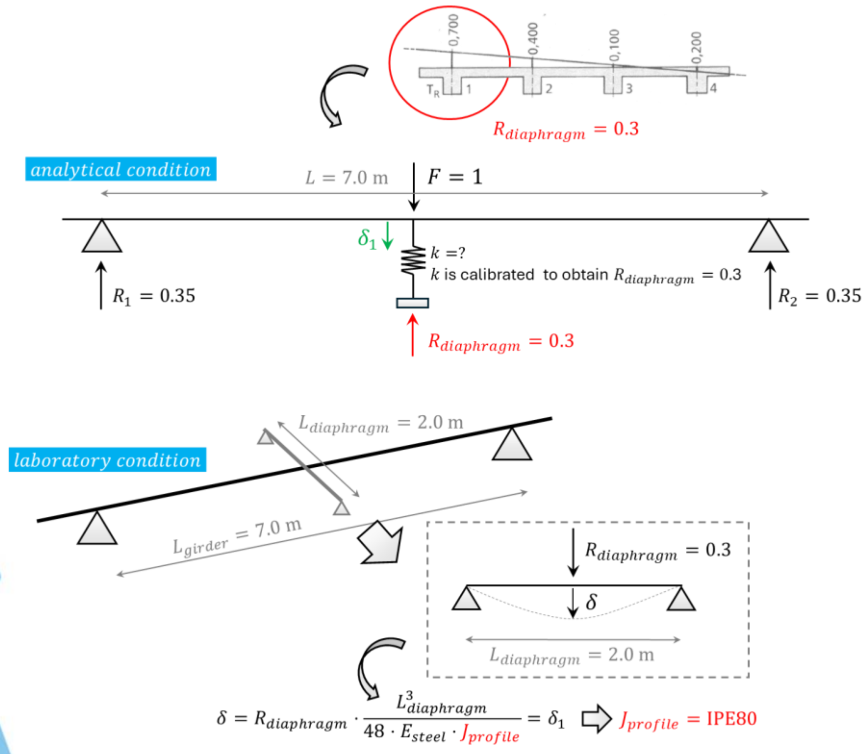


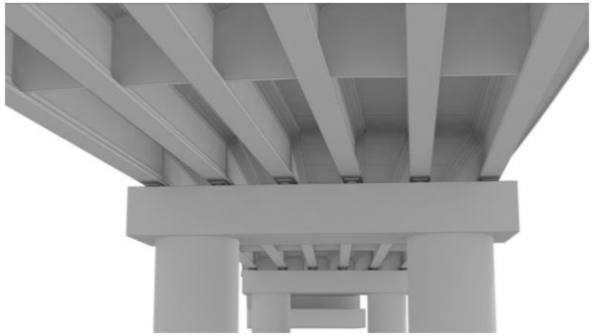


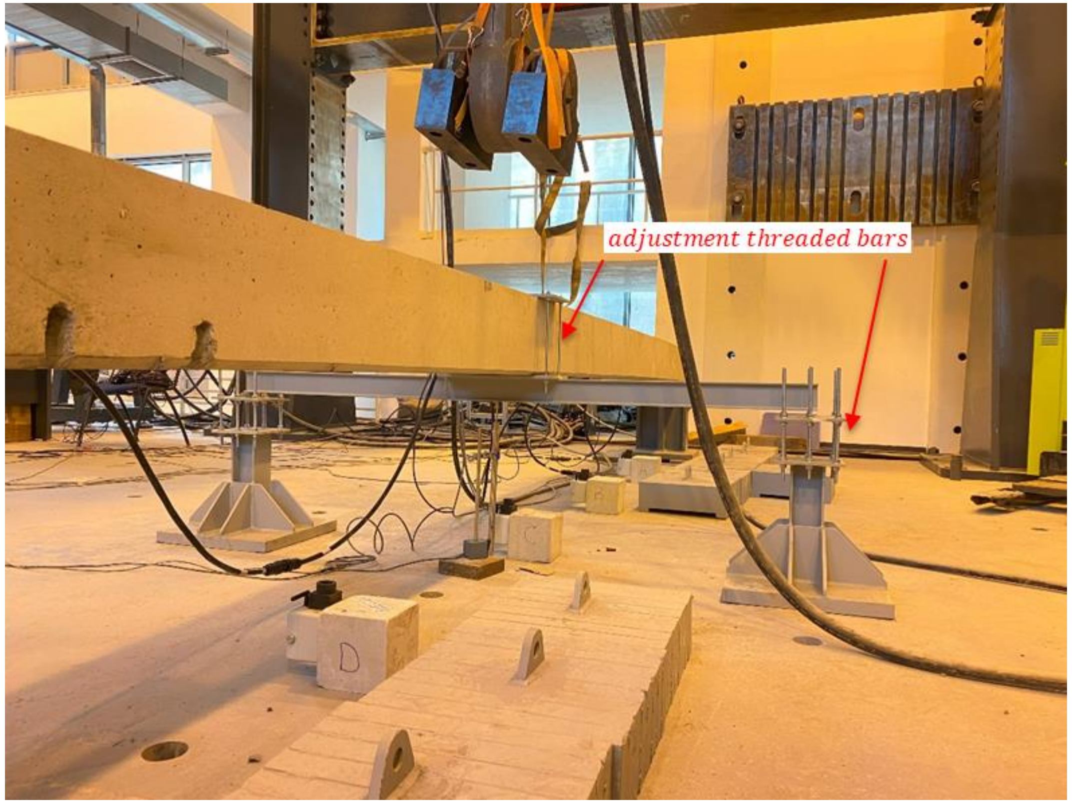
steel block 156 kg each



Simulation of the effect of transverse diaphragms

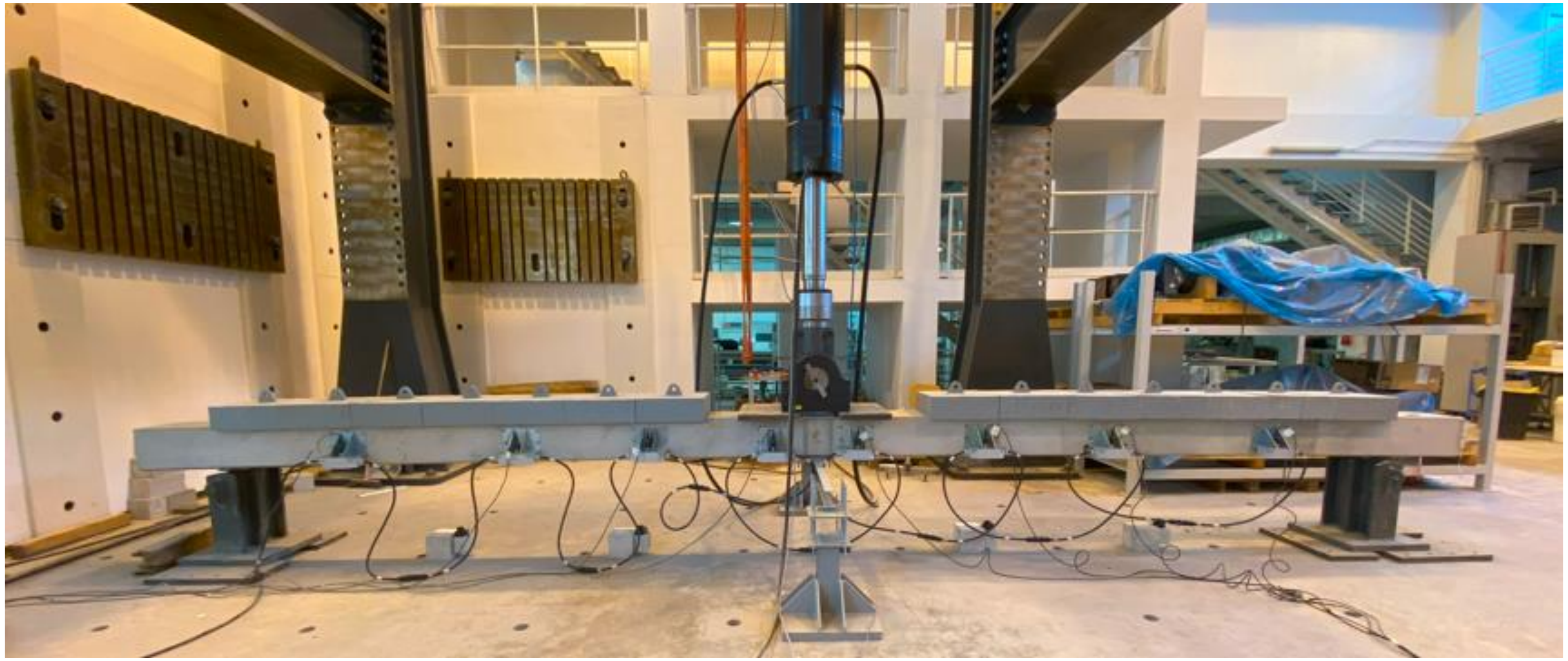


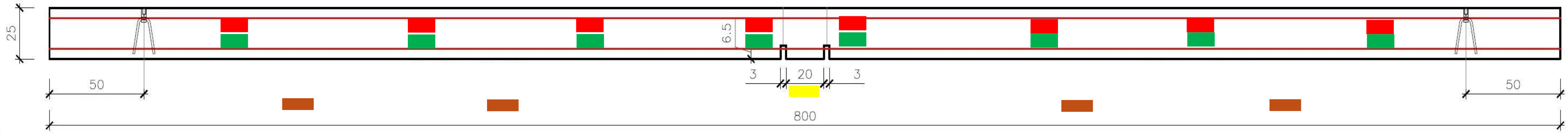




SENSORS' CONFIGURATION

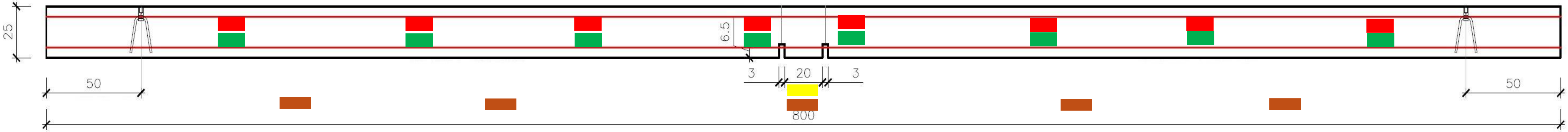
MEMS (3D Accelerometer + 2D inclinometer)
Piezoelectric sensor PCB (1D Accelerometer)
LVDT (for deflection measurements) + crack meters
LASER (for deflection measurements)

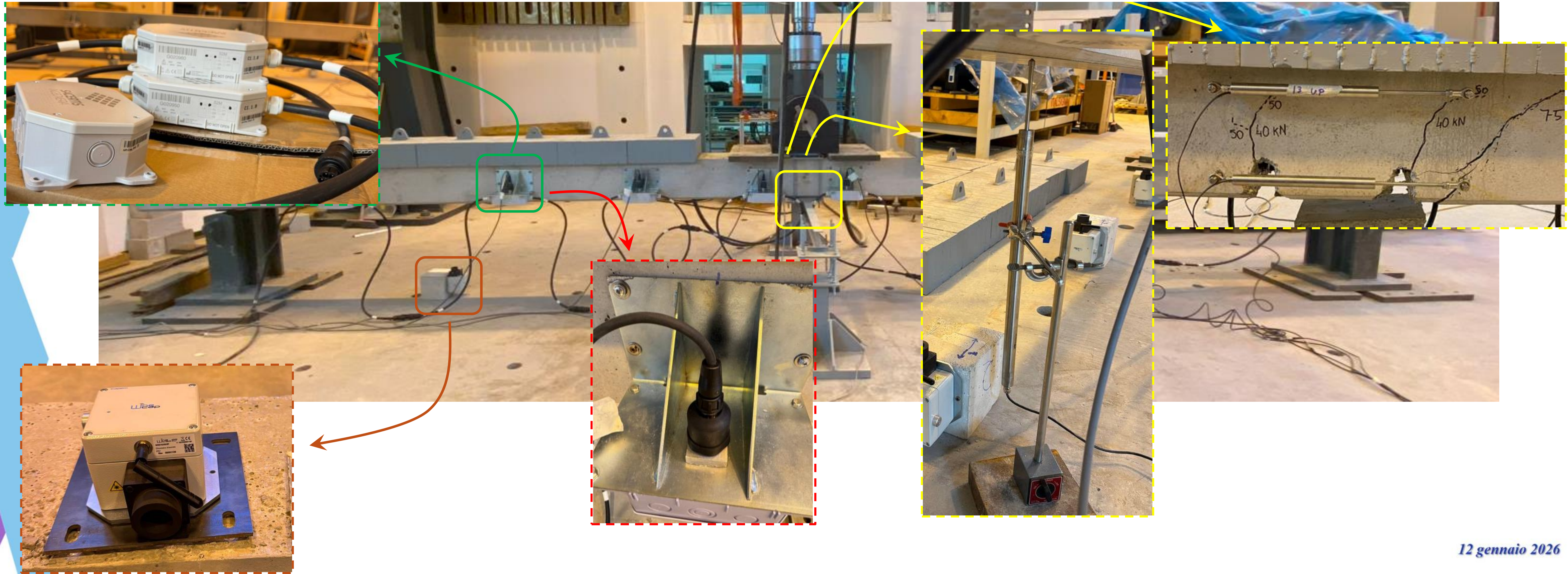




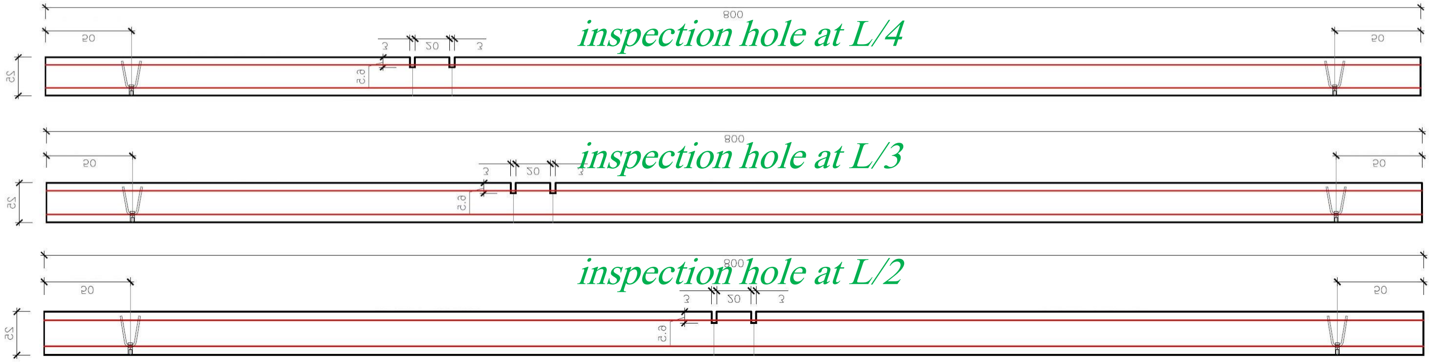
SENSORS' CONFIGURATION

- MEMS (3D Accelerometer + 2D inclinometer)
- Piezoelectric sensor PCB (1D Accelerometer)
- LVDT (for deflection measurements) + crack meters
- LASER (for deflection measurements)



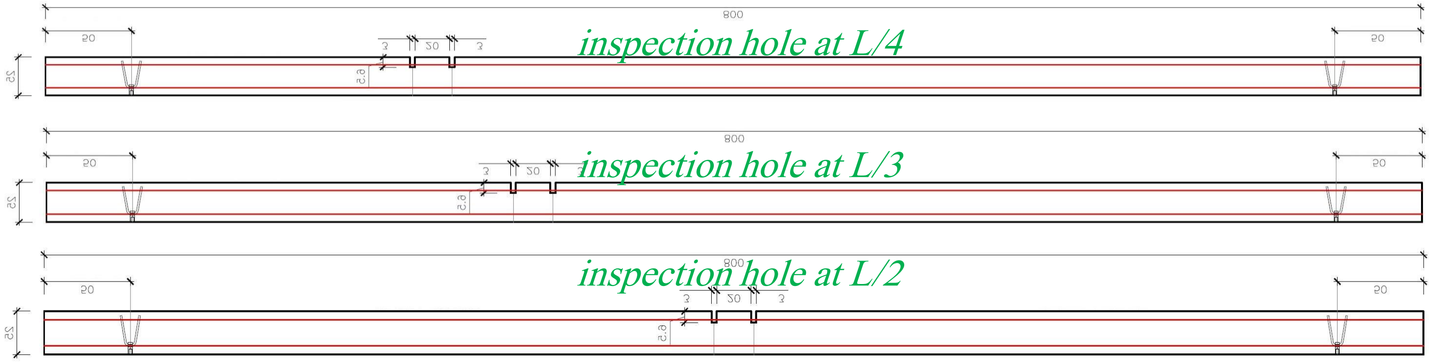


Test Matrix: Bonded & Unbonded Prestressed Beams: Tendon-Cut Damage Scenarios



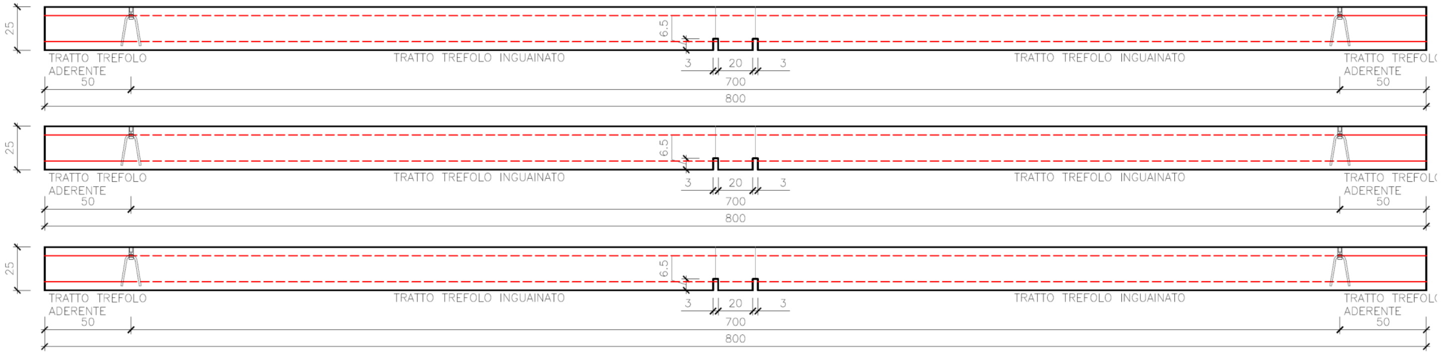
Bonded Beams
First set: with two-tendon cut damage scenario

D_L_4_2 with 2 cuts
D_L_3_2 with 2 cuts
D_L_2_2 with 2 cuts



Bonded Beams
Second set: with three tendon cut damage scenario

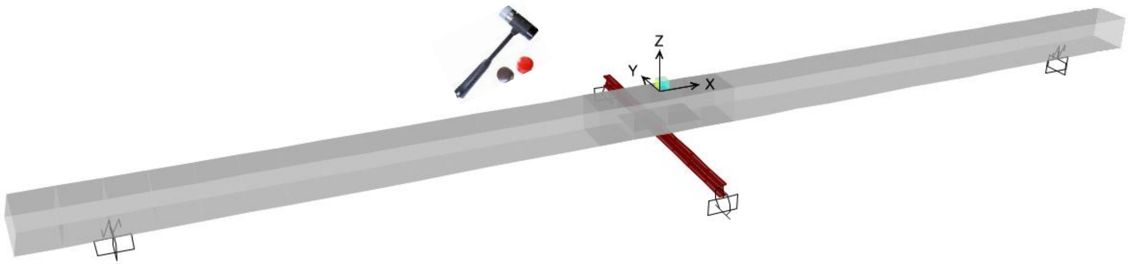
D_L_4_3 with 3 cuts
D_L_3_3 with 3 cuts
D_L_2_3 with 3 cuts



Unbonded Beams
Third set: damage scenario

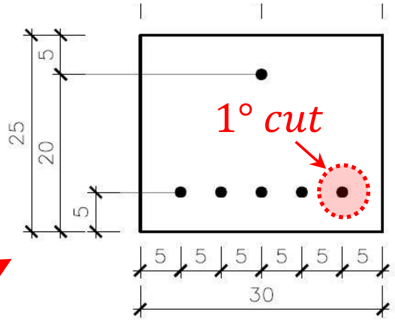
UB_UD without damage
UB_1 with one strand cut
UB_2 with two strand cuts

LOADING CONFIGURATION FOR SLS

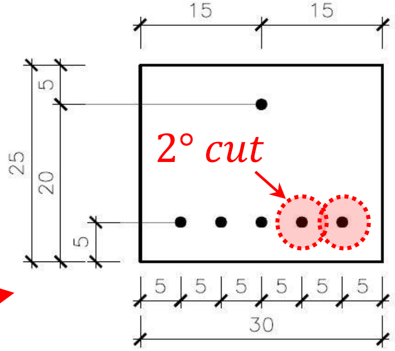


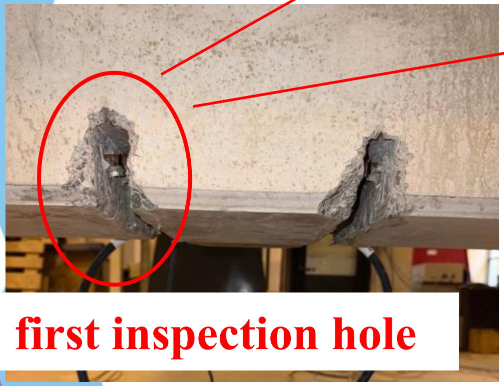
Damage simulation at serviceability conditions with transverse beam

dynamic test



15kN loading & unloading, dynamic test



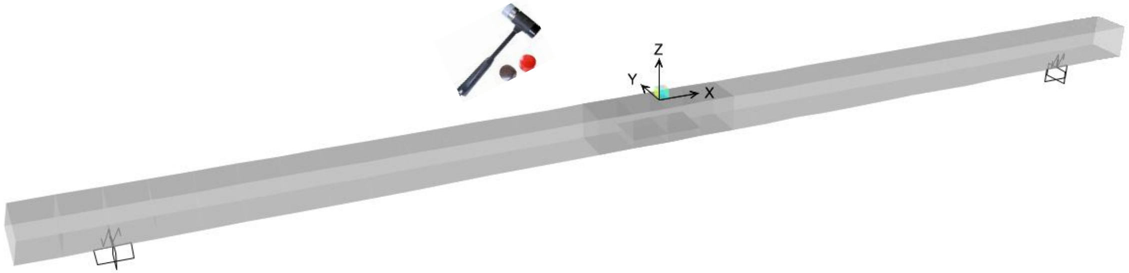


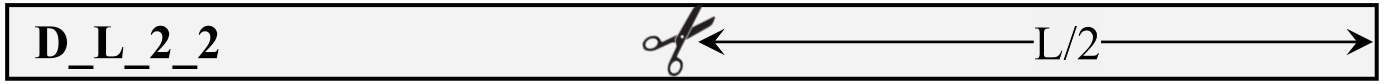
first inspection hole

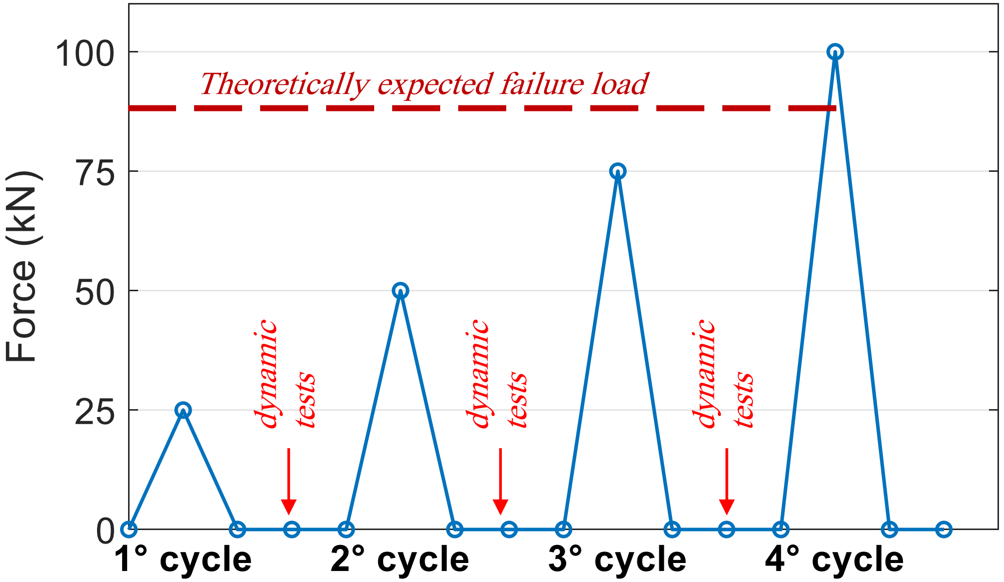
Repeat for the second inspection hole (2+2 cuts)

LOADING CONFIGURATION FOR ULS

Damage simulation at ultimate limit states
w/o transverse beam

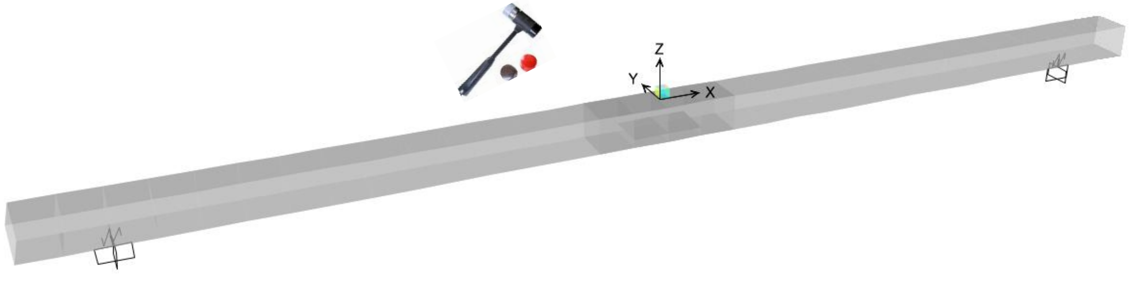


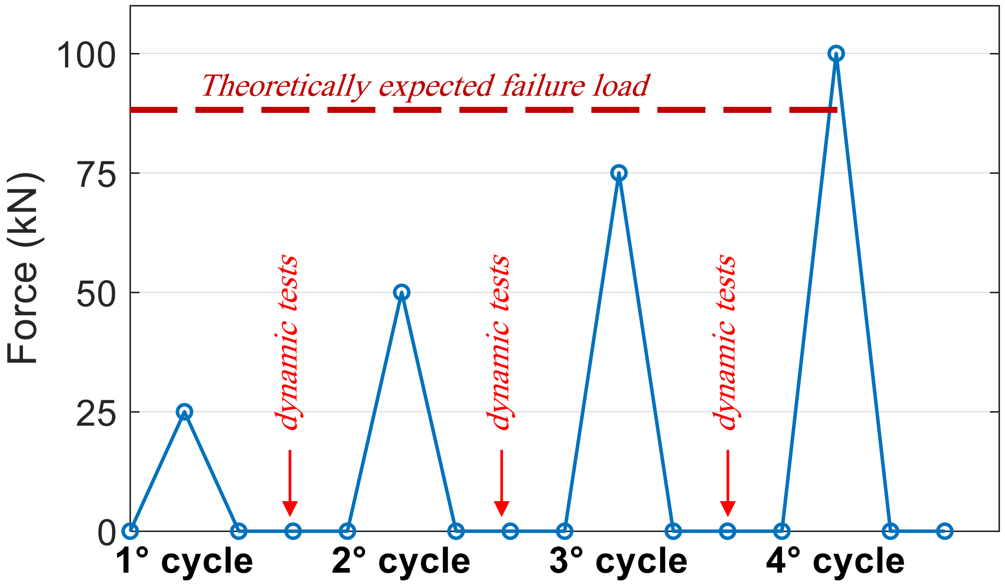


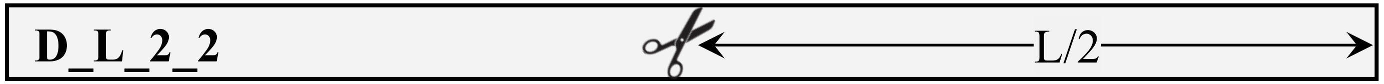


LOADING CONFIGURATION FOR ULS

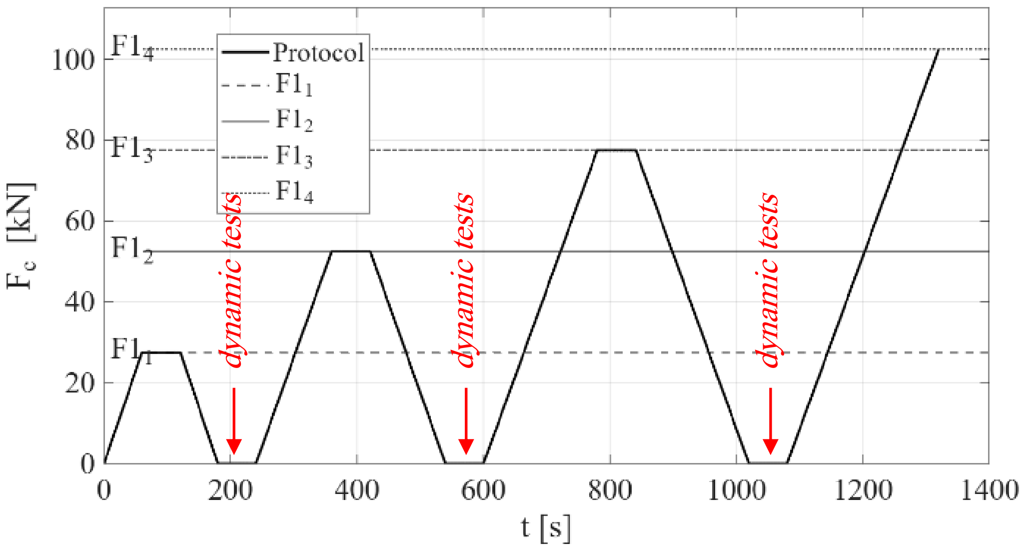
Damage simulation at ultimate limit states
w/o transverse beam

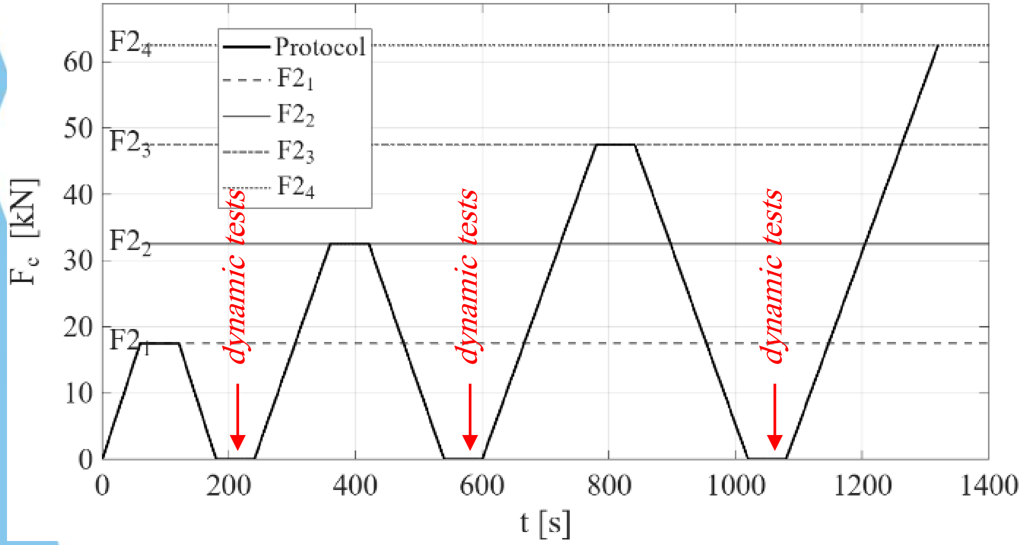




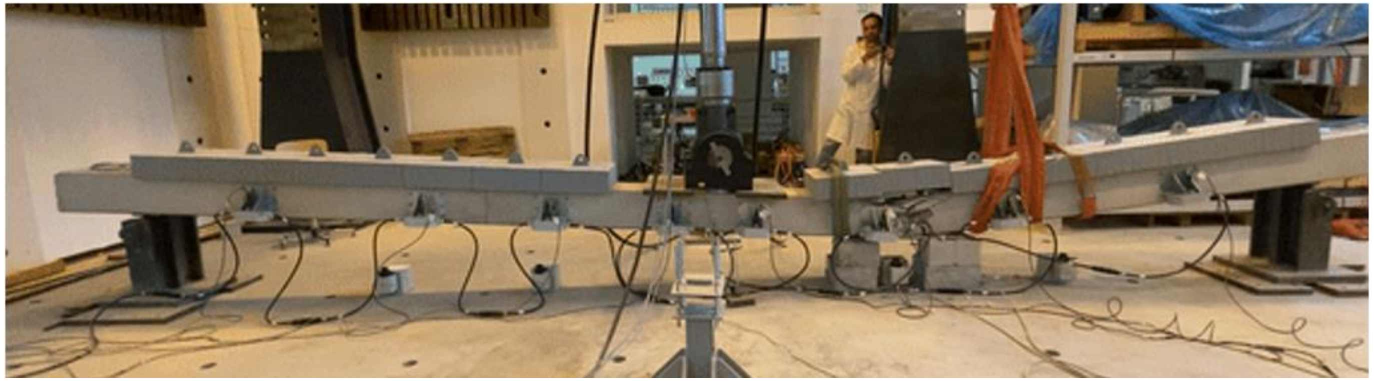


LOADING CONFIGURATION FOR ULS

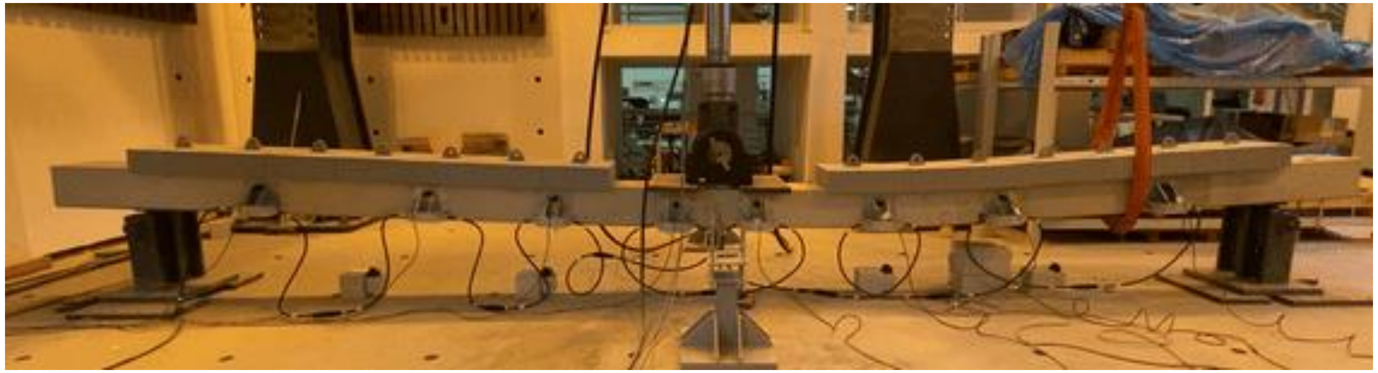




D_L_2_2 ← L/2 →

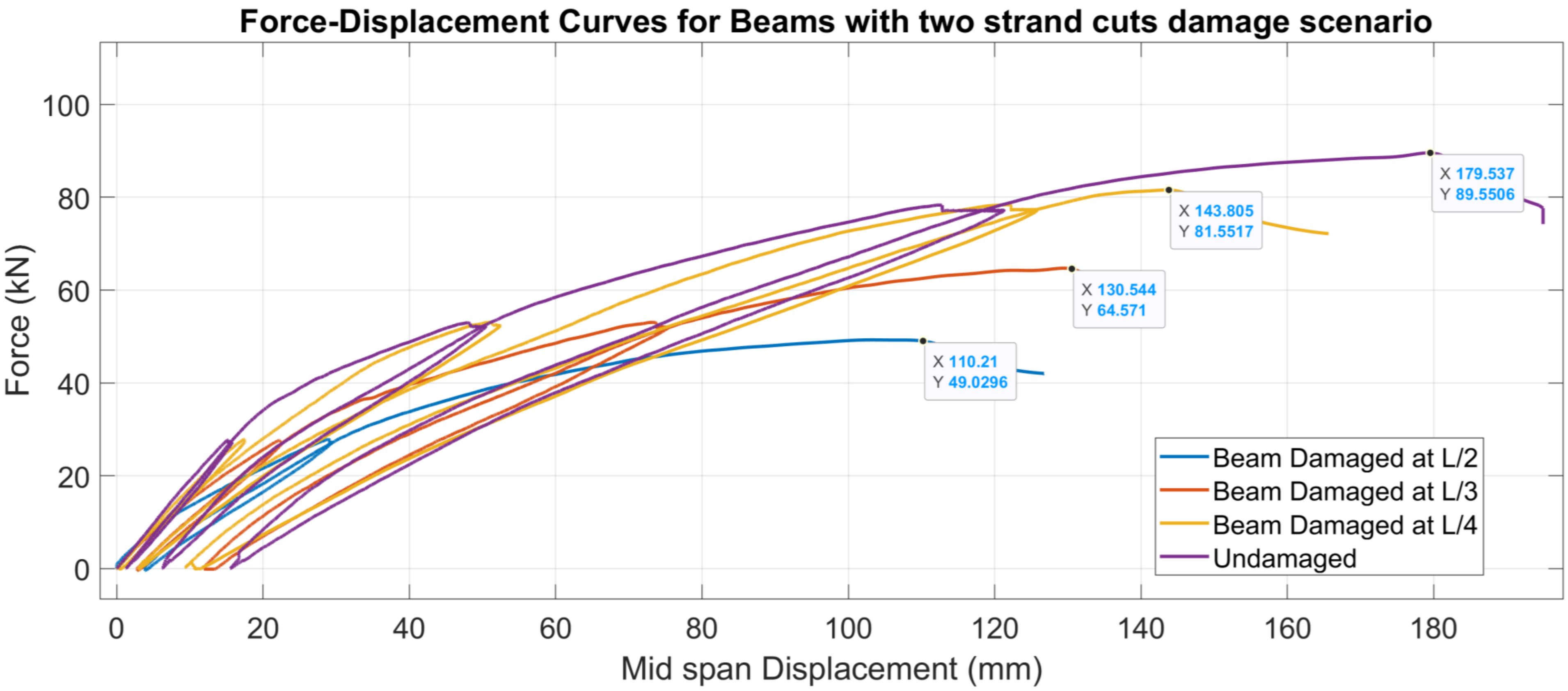


D_L_3_2 ← L/3 →



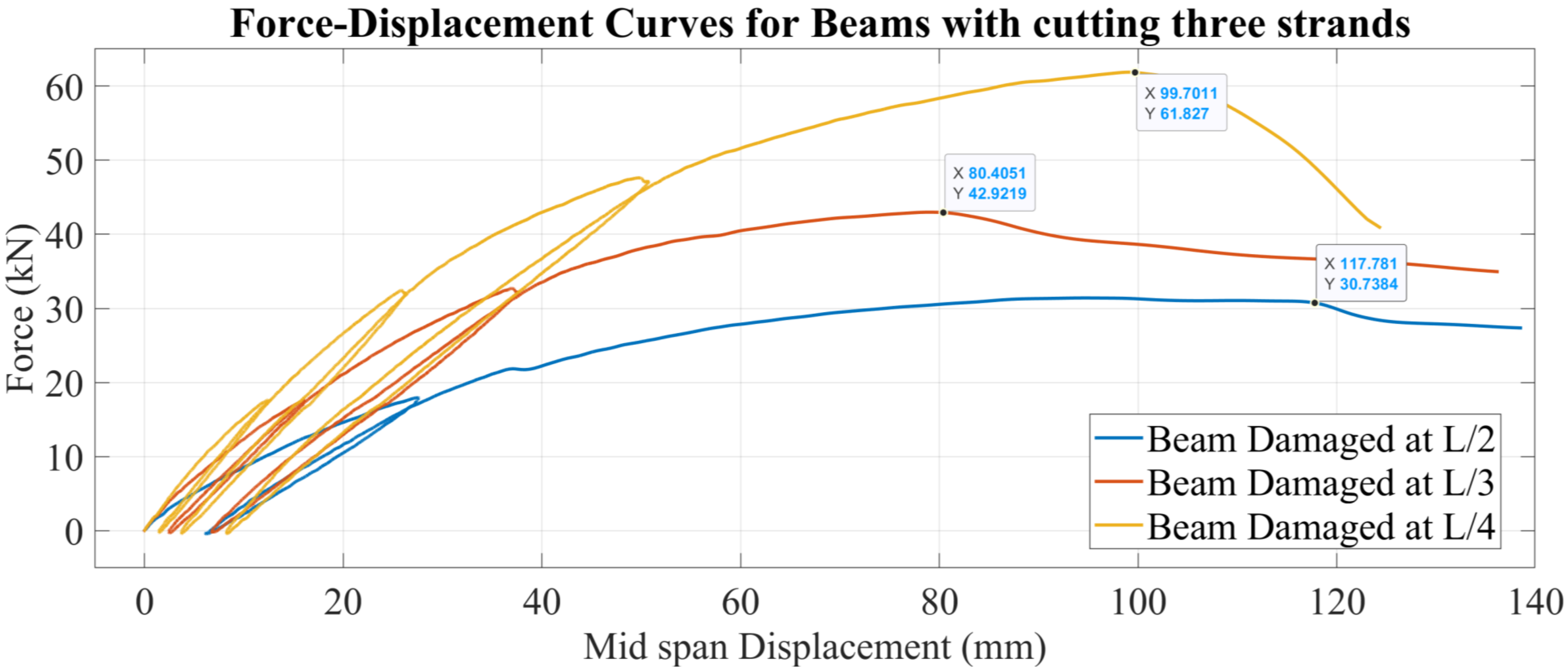
D_L_4_2 ← L/4 →

Frist set



Beam ID	P_{MAX} (kN)	Disp @ P_{MAX} (mm)	Δp (%)	Δ disp (%)
Undamaged (UD)	89.55	179.12	-	
D_L_4_2	81.56	143.55	-8.9	-19.9
D_L_3_2	64.71	129.39	-27.7	-27.8
D_L_2_2	49.27	103.13	-45.0	-42.4

Second set

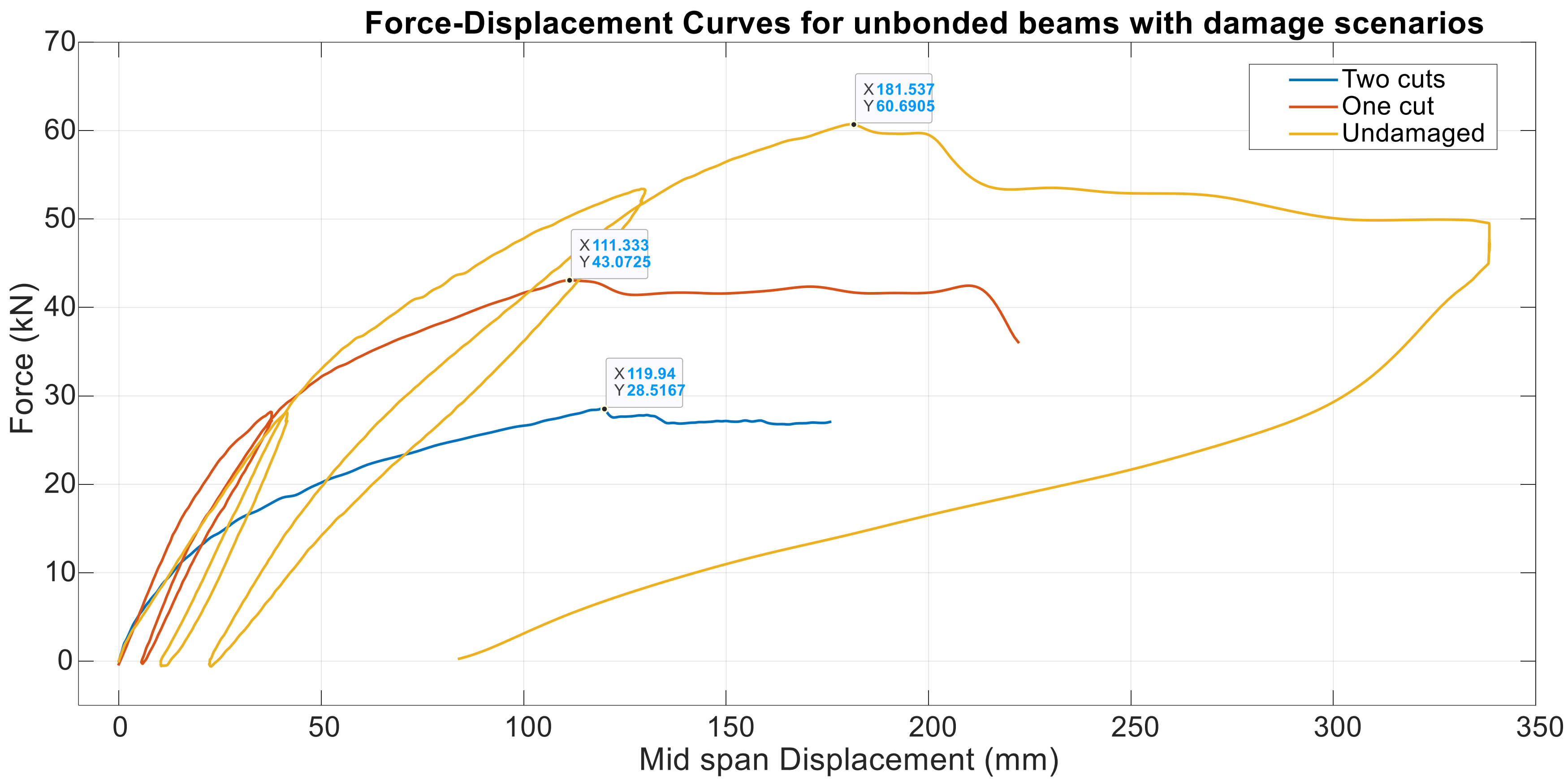


Beam ID	P_{MAX} (kN)	Disp @ P_{MAX} (mm)	Δp (%)	Δ disp (%)
Undamaged (UD)	89.55	179.12	-	
D_L_4_3	61.82	99.70	-30.96	-44.33
D_L_3_3	42.92	80.40	-52.07	-55.11
D_L_2_3	30.73	117.78	-65.68	-34.24

Comparison of the Force–Displacement Response at Mid-Span for Two Different Damage Scenarios : Frist & Second set

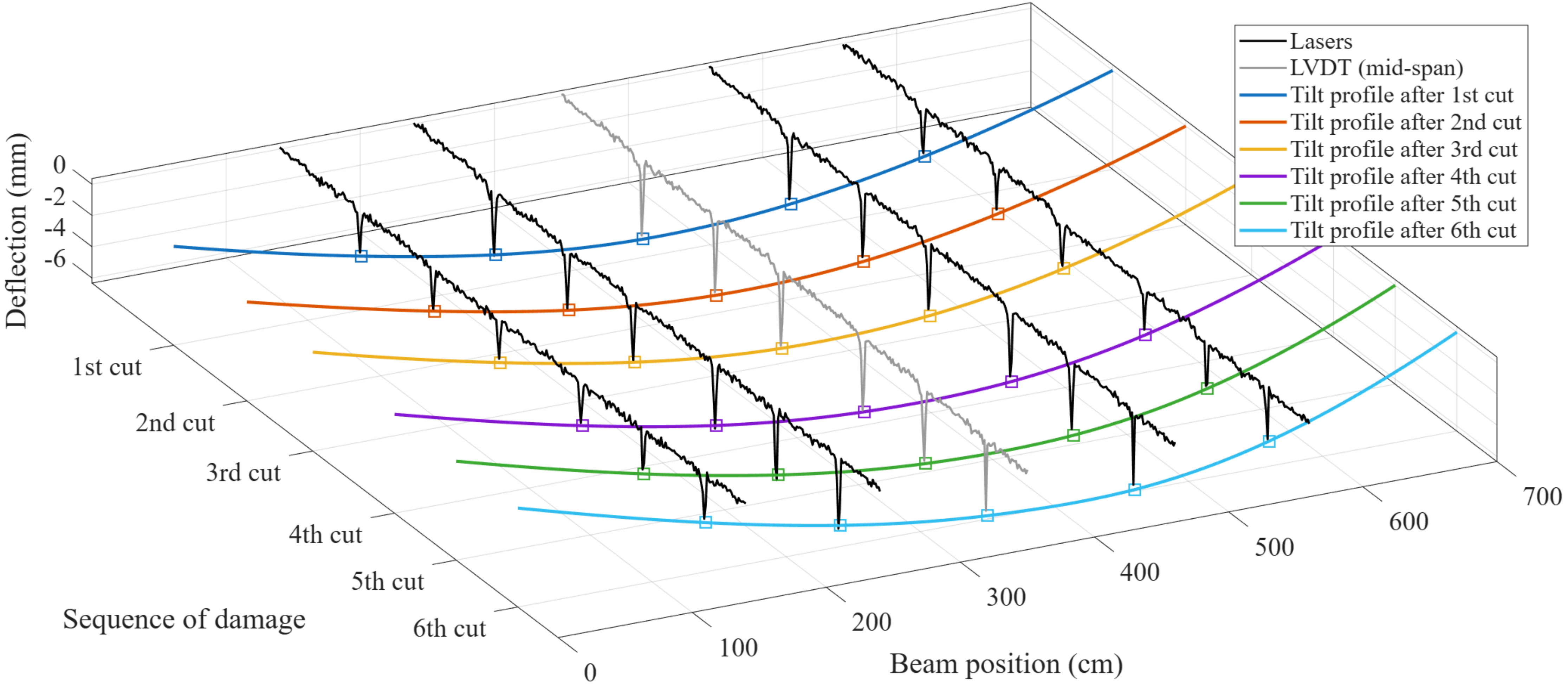
Beam ID	P_{MAX} (kN)	Disp @ P_{MAX} (mm)	Δp (%)	Δ disp (%)
Undamaged (UD)	89.55	179.12	-	
D_L_4_2	81.56	143.55	-8.9	-19.9
D_L_4_3	61.82	99.70	-30.96	-44.33
D_L_3_2	64.71	129.39	-27.7	-27.8
D_L_3_3	42.92	80.40	-52.07	-55.11
D_L_2_2	49.27	103.13	-45.0	-42.4
D_L_2_2	30.73	117.78	-65.68	-34.24

Third set



Beam ID	P_{MAX} (kN)	Disp @ P_{MAX} (mm)	Δp (%)	Δ disp (%)
Undamaged (UD)	89.55	179.12	-	
UB_UD	60.69	181.53	-32.22	+1.34
UB_1	43.07	111.33	-29.03	-38.67
UB_2	28.51	119.94	-53.02	-33.92

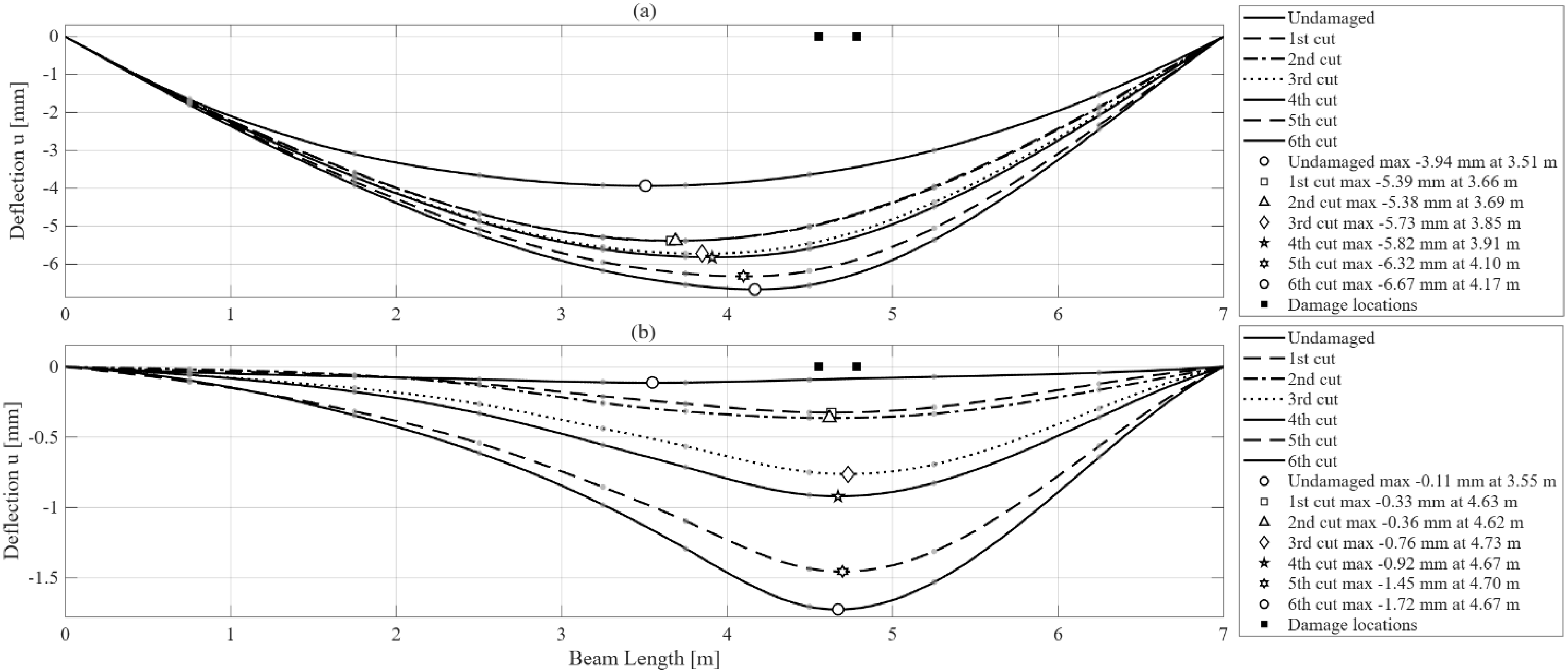
Tilt derived deflection profile validation with Lasers and LVDT



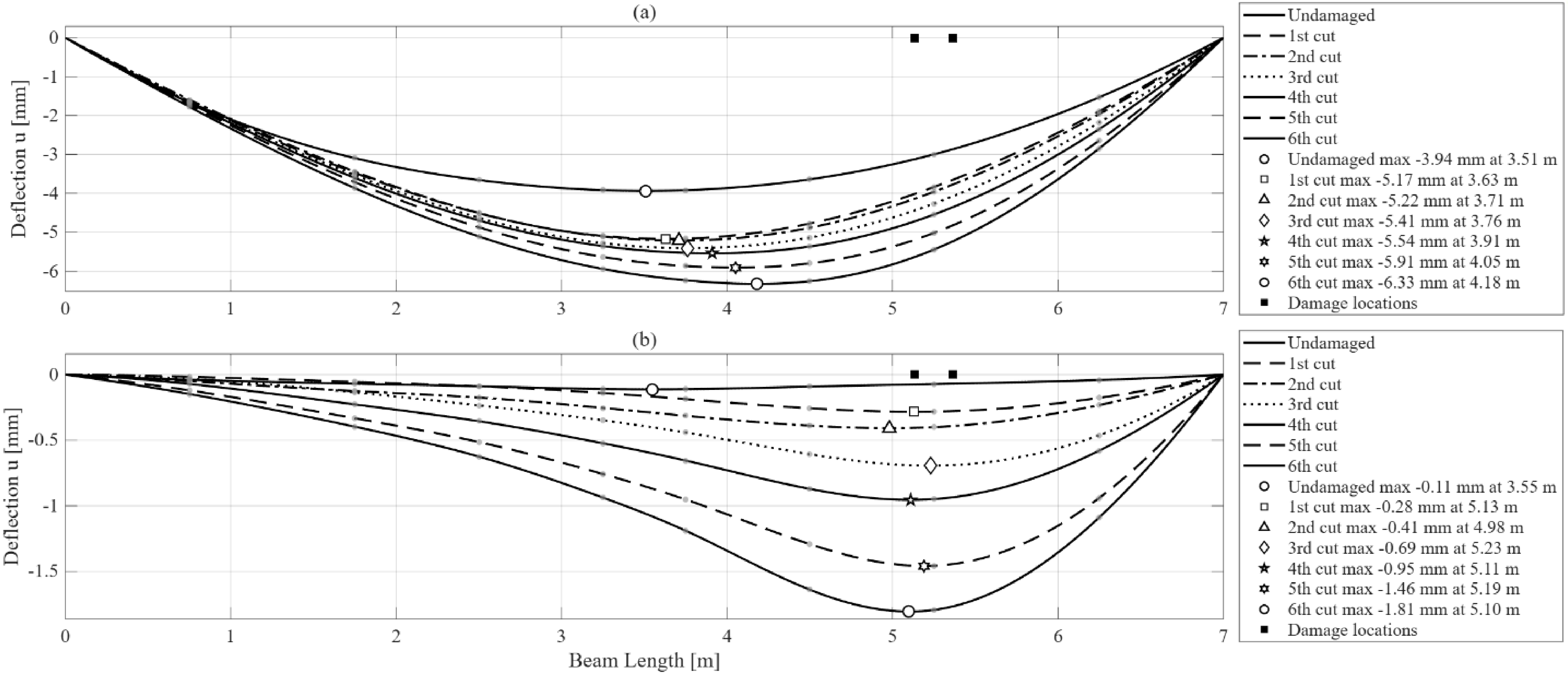
Tilt derived deflection profile validation with Lasers and LVDT

Damage\position	Laser A (1.4m)	Laser B (2.4m)	LVDT (3.5m)	Laser D (4.6m)	Laser E (5.6m)
1-Cut laser-LVDT	-2.71 mm	-4.53 mm	-5.08 mm	-4.45 mm	-3.11 mm
1-Cut Tilt	-2.88 mm	-4.39 mm	-5.16 mm	-4.68 mm	-3.24 mm
1-Cut Error (%)	6.3%	3.1%	1.6%	5.2%	4.1%
2-Cuts laser-LVDT	-2.90 mm	-4.30 mm	-5.11 mm	-4.59 mm	-3.16 mm
2-Cuts Tilt	-2.84 mm	-4.38 mm	-5.19 mm	-4.79 mm	-3.35 mm
2-Cuts Error (%)	2.1%	1.9%	1.6%	4.4%	6.0%
3-Cuts laser-LVDT	-2.74 mm	-4.53 mm	-5.29 mm	-4.71 mm	-3.56 mm
3-Cuts Tilt	-2.92 mm	-4.50 mm	-5.37 mm	-5.05 mm	-3.65 mm
3-Cuts Error (%)	6.6%	0.7%	1.5%	7.2%	2.5%
4-Cuts laser-LVDT	-2.86 mm	-4.83 mm	-5.44 mm	-5.04 mm	-3.66 mm
4-Cuts Tilt	-2.98 mm	-4.57 mm	-5.47 mm	-5.29 mm	-3.92 mm
4-Cuts Error (%)	4.2%	5.4%	0.6%	5.0%	7.1%
5-Cuts laser-LVDT	-2.85 mm	-5.13 mm	-5.71 mm	-5.41 mm	-4.26 mm
5-Cuts Tilt	-3.06 mm	-4.73 mm	-5.78 mm	-5.74 mm	-4.36 mm
5-Cuts Error (%)	7.4%	7.8%	1.2%	6.1%	2.4%
6-Cuts laser-LVDT	-3.00 mm	-5.23 mm	-5.98 mm	-5.97 mm	-4.66 mm
6-Cuts Tilt	-3.18 mm	-4.96 mm	-6.11 mm	-6.20 mm	-4.72 mm
6-Cuts Error (%)	6.0%	5.2%	2.2%	3.9%	1.3%
MAPE (%)	5.4%	4.0%	1.5%	5.3%	3.9%

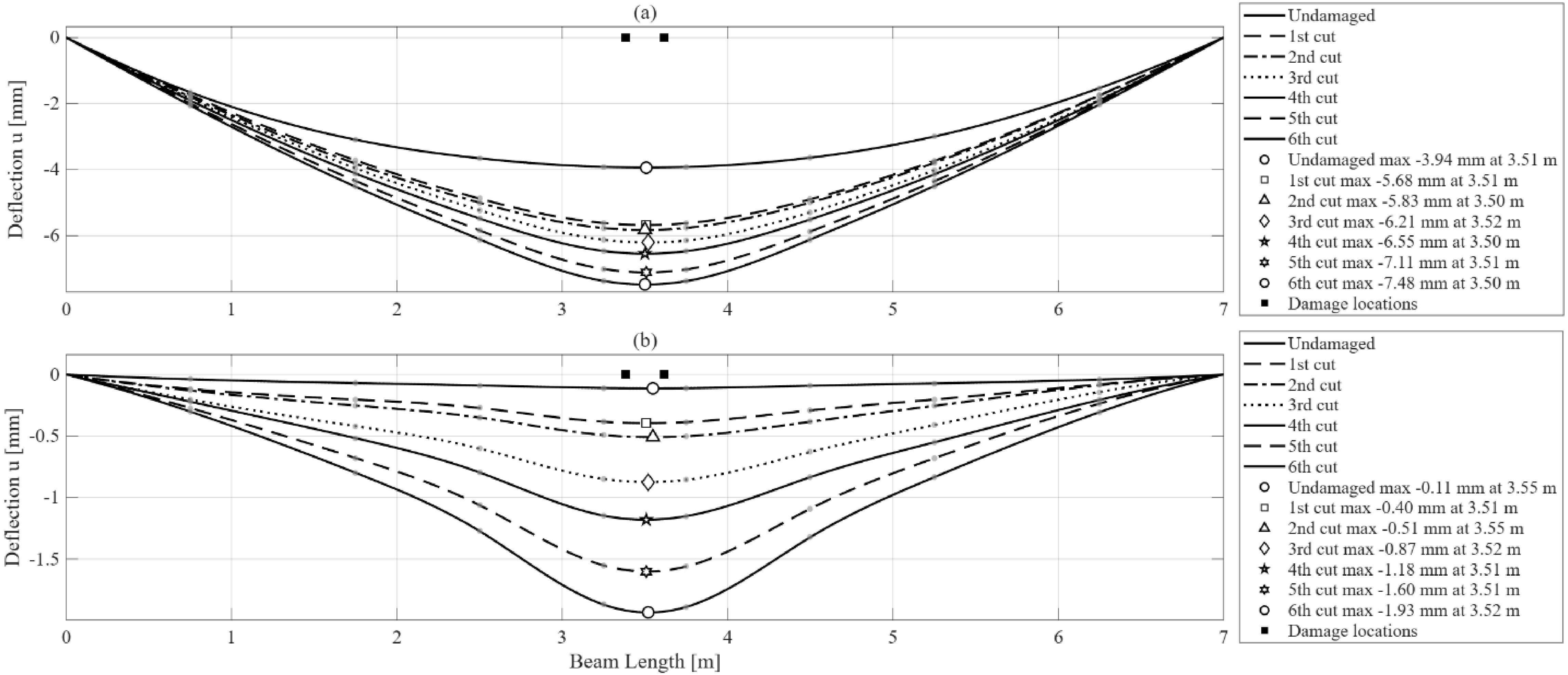
D_L_3_3 deflection profile from tilt during loading of 15 kN at mid-span (a) and unloading (b)



D_L_4_3 deflection profile from tilt during loading of 15 kN at mid-span (a) and unloading (b)



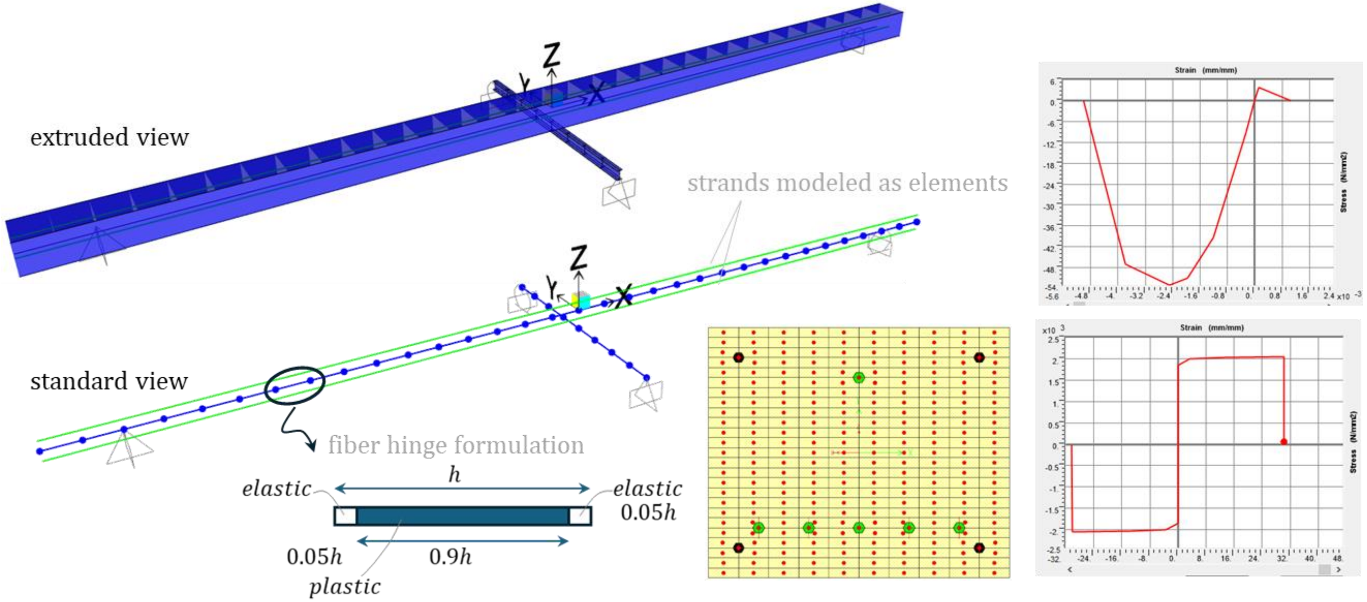
D_L_2_3 deflection profile from tilt during loading of 15 *kN* at mid-span (a) and unloading (b)

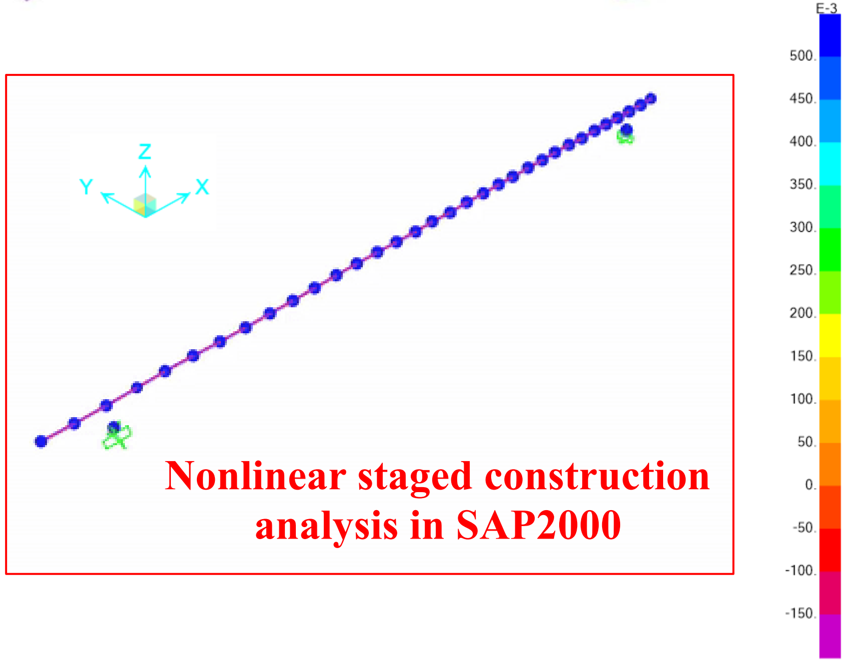


Comparison of the residual deflection and related location for the second damage scenario with increasing damage

Damage/Beam type	D_L/2_3 damage at $x = 3.5\mathrm{m}$		D_L/3_3 damage at $x = 4.67\mathrm{m}$		D_L/4_3 damage at $x = 5.25\mathrm{m}$	
	$u_{res}^{max}(mm)$	$x_{max}^{load}(m)$	$u_{res}^{max}(mm)$	$x_{max}^{load}(m)$	$u_{res}^{max}(mm)$	$x_{max}^{load}(m)$
After 1 cut	-0.40	3.51	-0.33	4.63	-0.28	5.13
After 2 cuts	-0.51	3.55	-0.36	4.62	-0.41	4.98
After 3 cuts	-0.87	3.52	-0.76	4.73	-0.66	5.23
After 4 cuts	-1.18	3.51	-0.92	4.67	-0.95	5.11
After 5 cuts	-1.60	3.51	-1.45	4.70	-1.46	5.19
After 6 cuts	-1.93	3.52	-1.72	4.67	-1.81	5.10

NUMERICAL MODELING





Mode shapes of PC beams with steel blocks w/o transverse beam

	Mode-1	Mode-2(L)	Mode-3(L)	Mode-4	Mode-5
Enhanced FEM	7.20	8.84	17.96	20.25	43.19
Undamaged_(MEMS)	7.17	8.43	18.16	19.54	44.25
FBG-undamaged	7.20	8.72	-	19.46	43.63

Curvature Damage Factor (CDF)

$$\mathrm{CDF} = \frac{1}{N}\sum_{i=1}^{N} \left| v''_{o,i} - v''_{d,i} \right|$$

Curvature Damage Factor (CDF)
N is total number of modes
v''_o is the undamaged curvature mode shape
v'_d is the damaged curvature mode shape

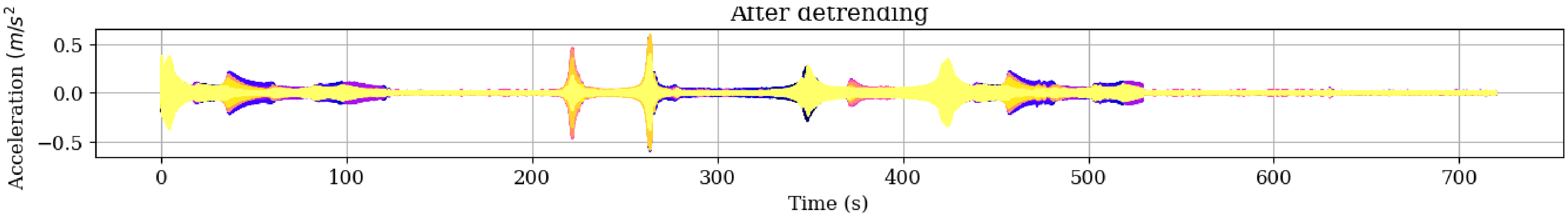
DAMAGE DETECTION IN BRIDGES USING MODAL CURVATURES: APPLICATION TO A REAL DAMAGE SCENARIO
by G. DE ROECK, M. M. ABDEL WAHAB, 1999, Journal of Sound and Vibration

$$\mathrm{SDF} = \frac{1}{N}\sum_{i=1}^{N} \left| v'_{o,i} - v'_{d,i} \right|$$

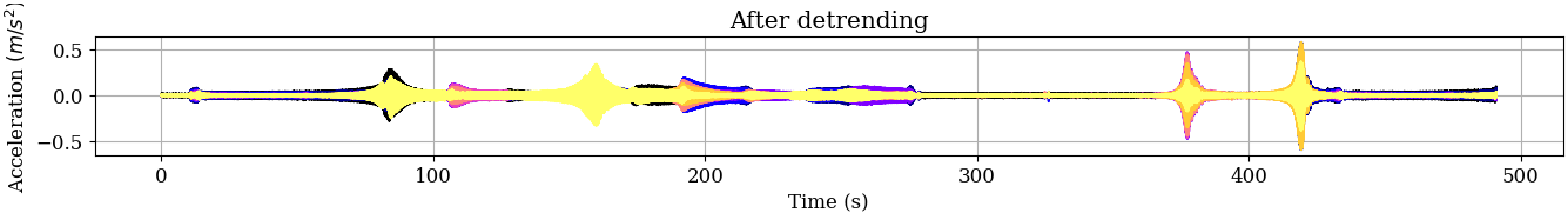
Slope Damage Factor (SDF)
N is total number of modes
v''_o is the undamaged slope mode shape
v'_d is the damaged slope mode shape

Time History of accelerations for MEMS & PCB

MEMS

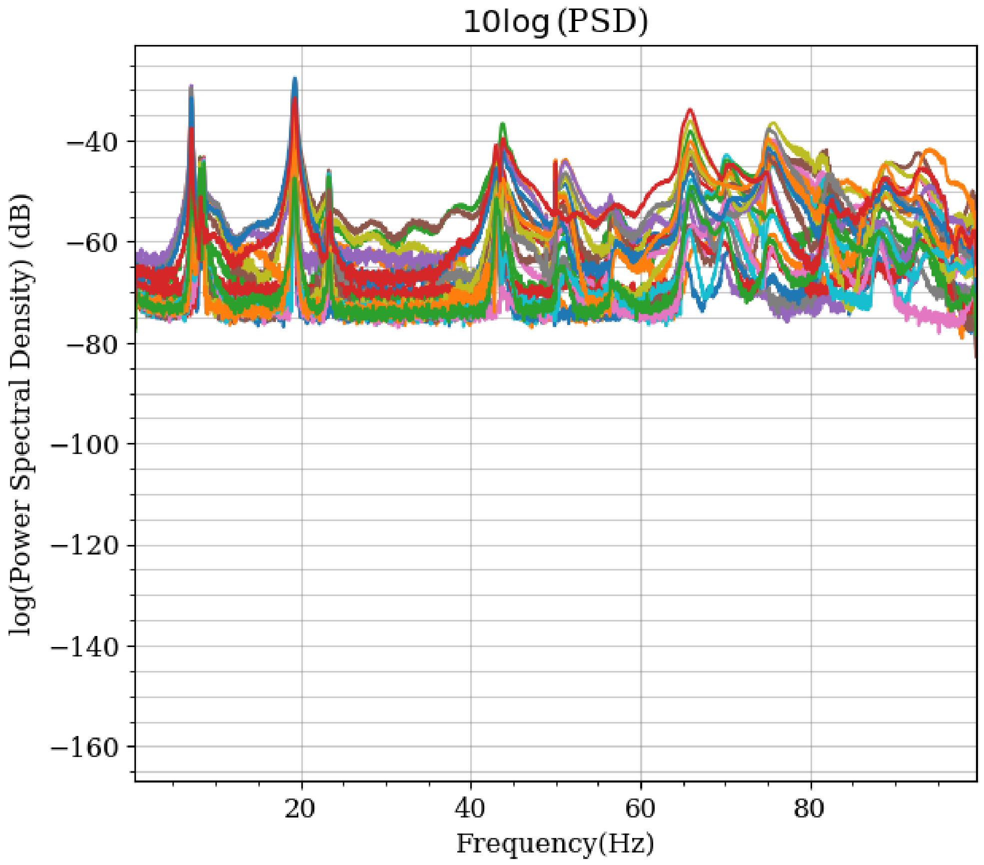


PCB

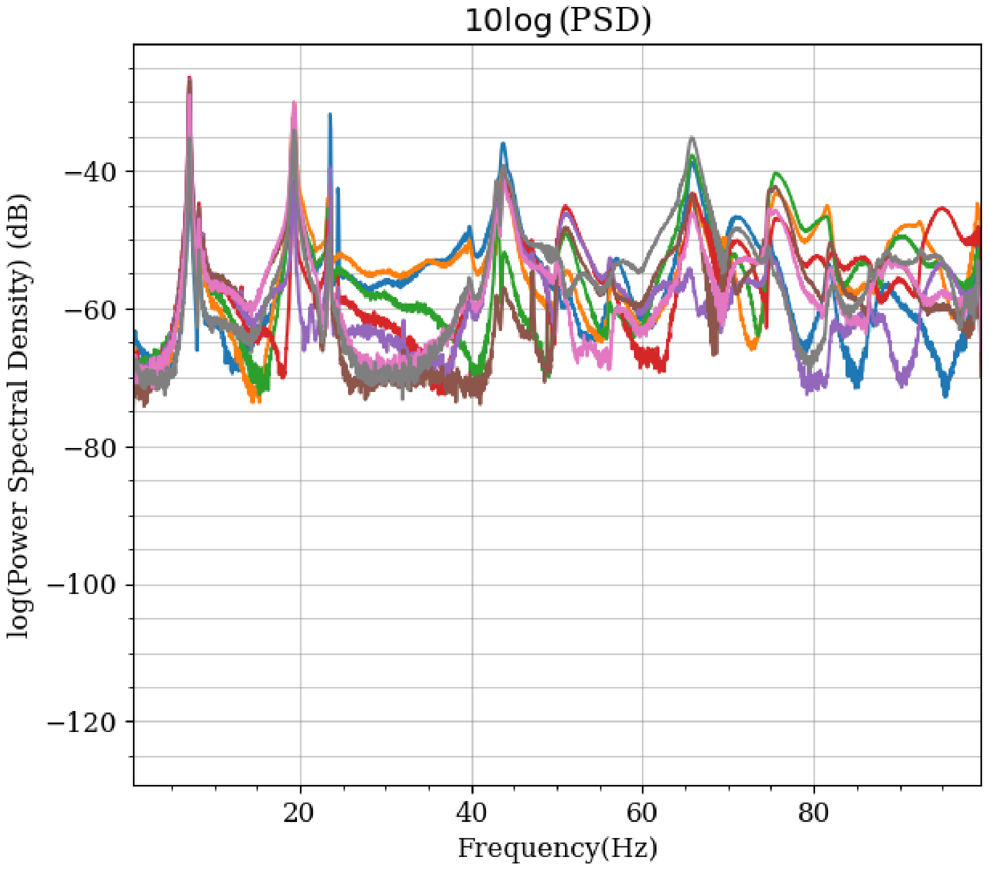


PSD comparison

MEMS

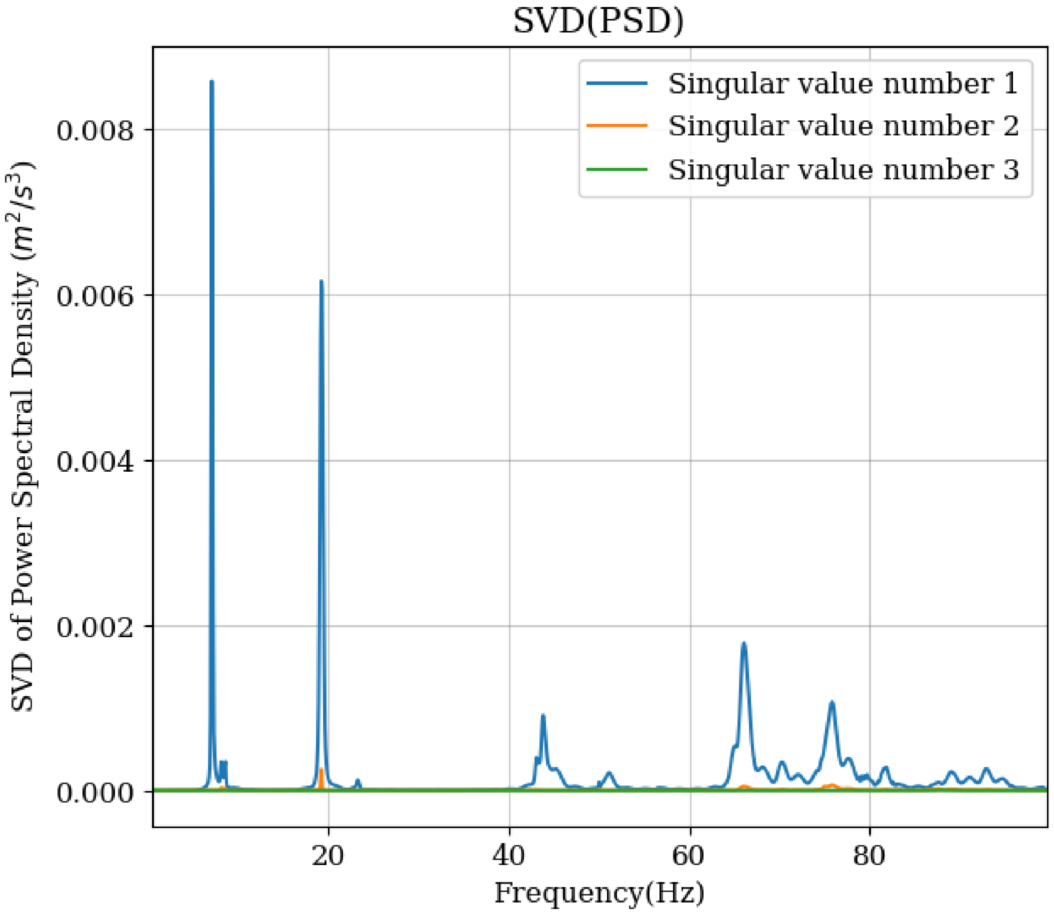


PCB

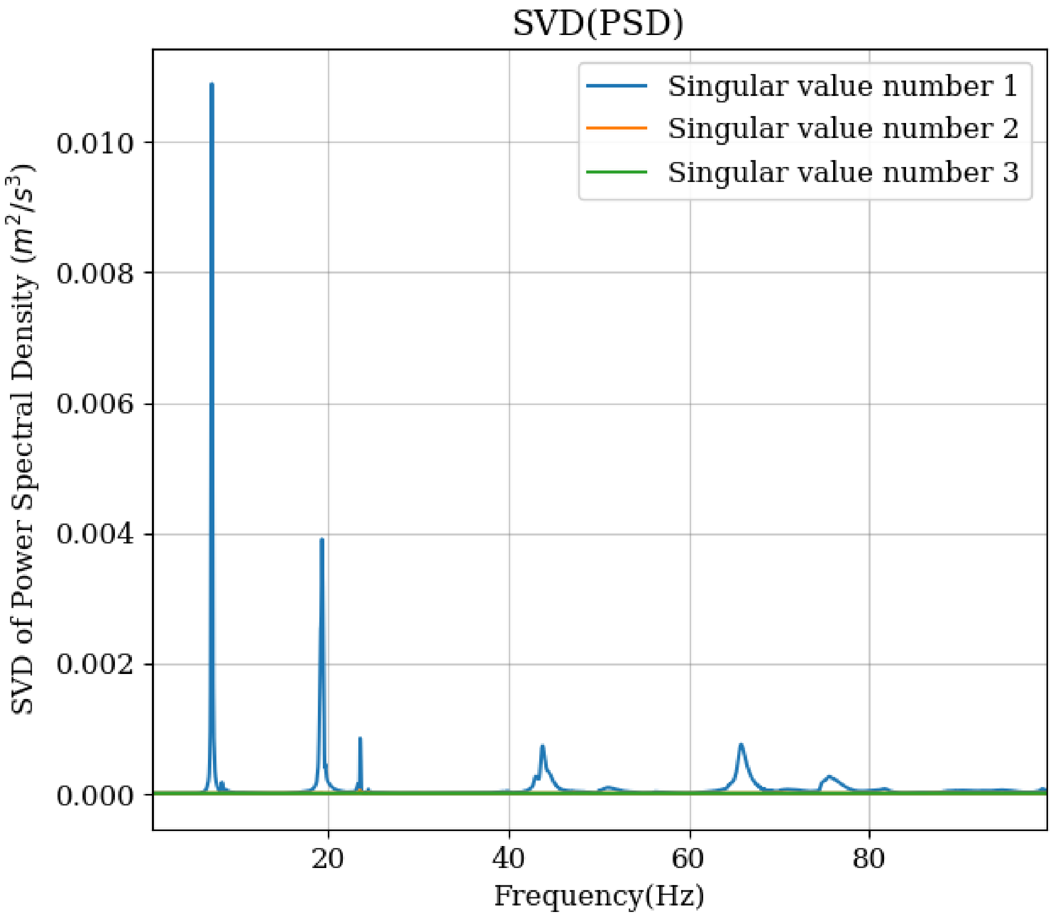


SVD comparison

MEMS

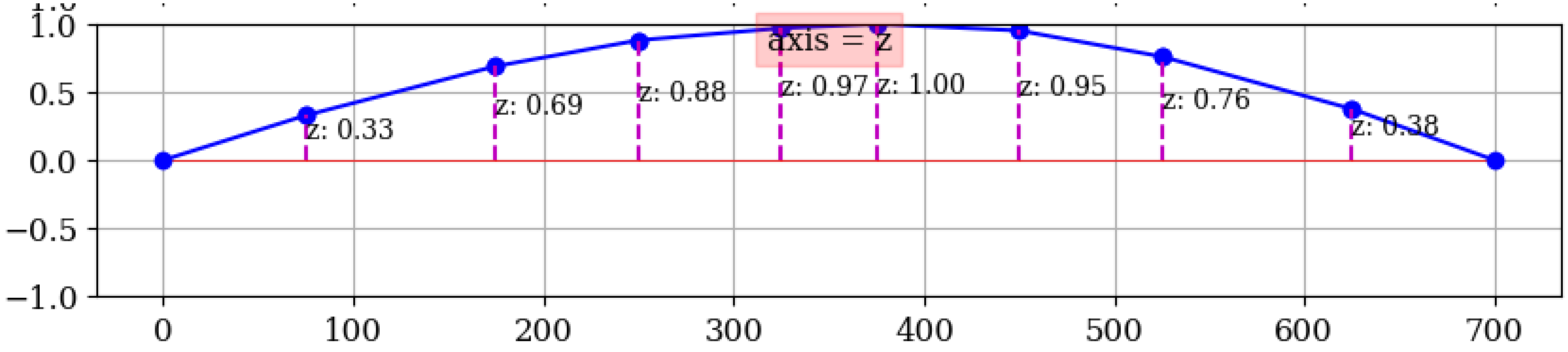


PCB

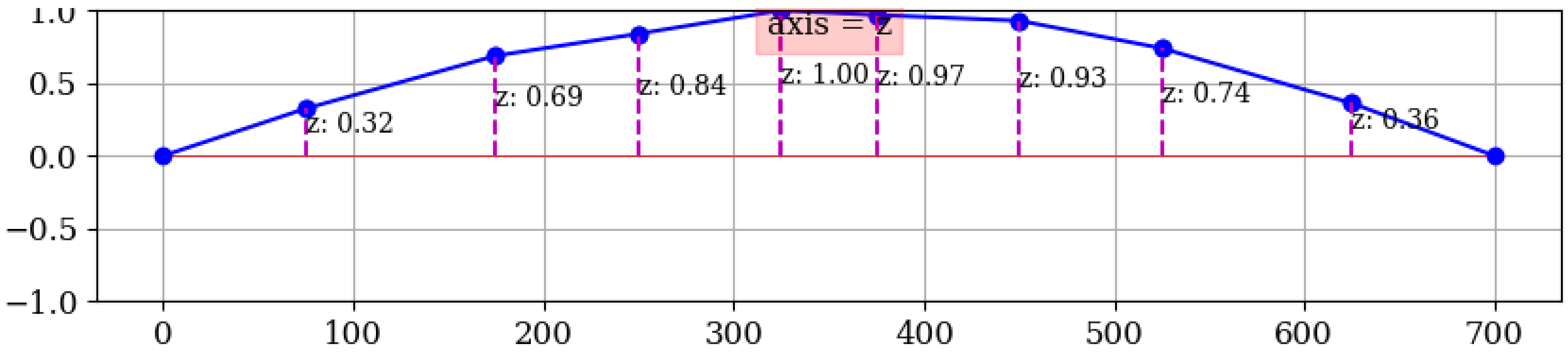


1st Bending mode (7.11 Hz)

MEMS

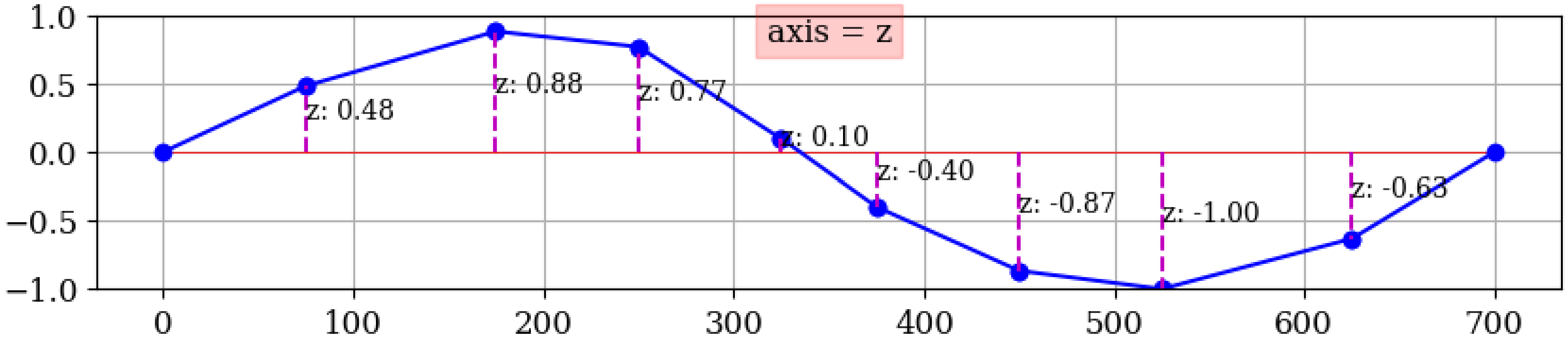


PCB

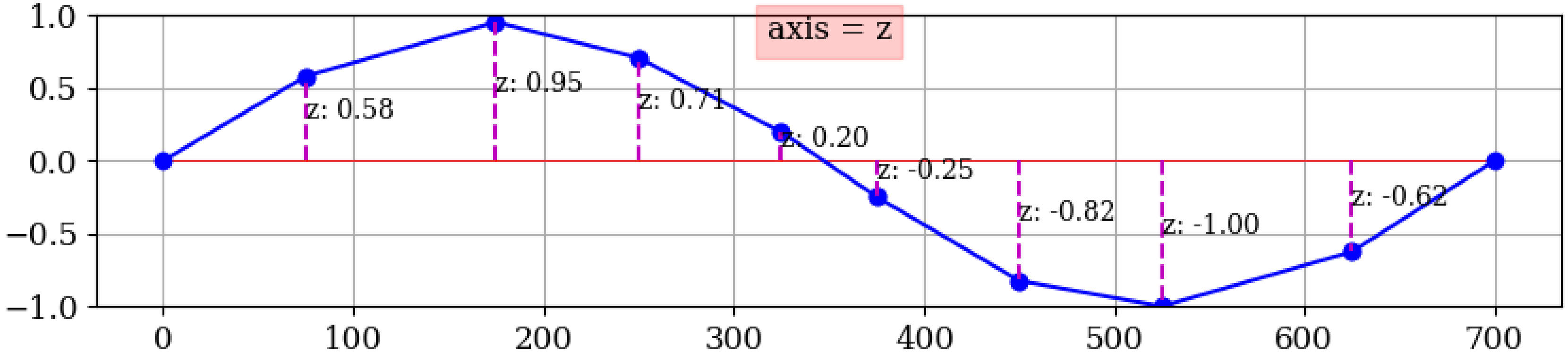


2nd Bending mode (19.31 Hz)

MEMS

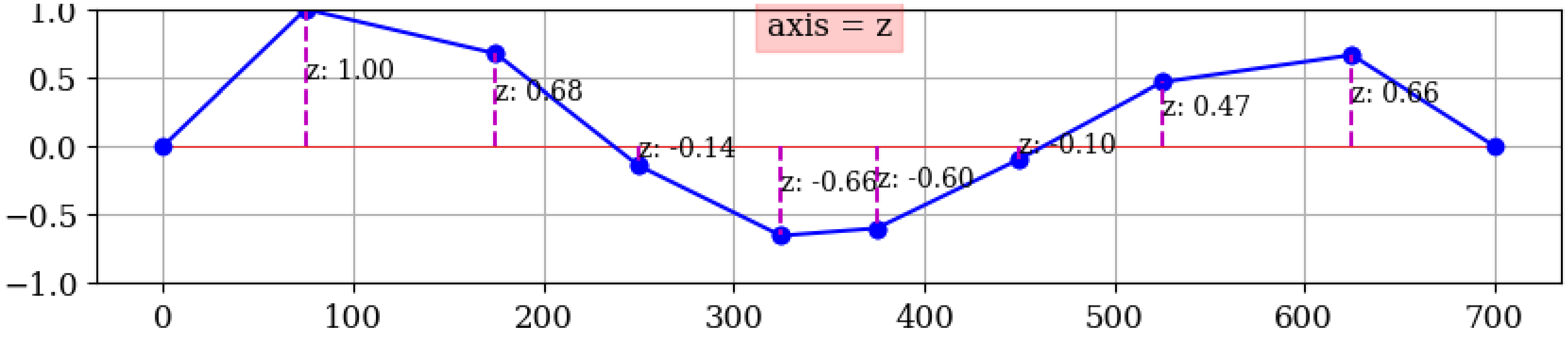


PCB

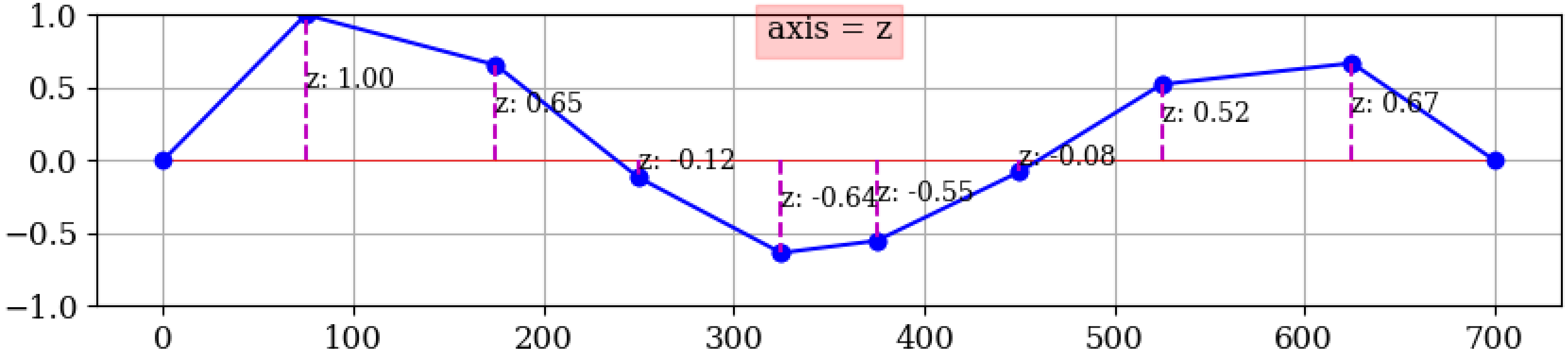


3rd Bending mode (43.76 Hz)

MEMS

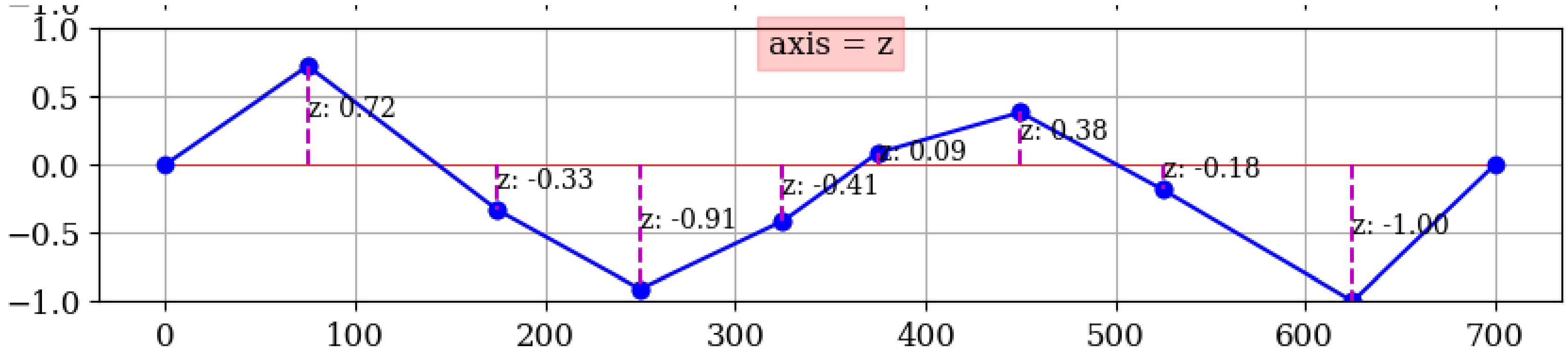


PCB

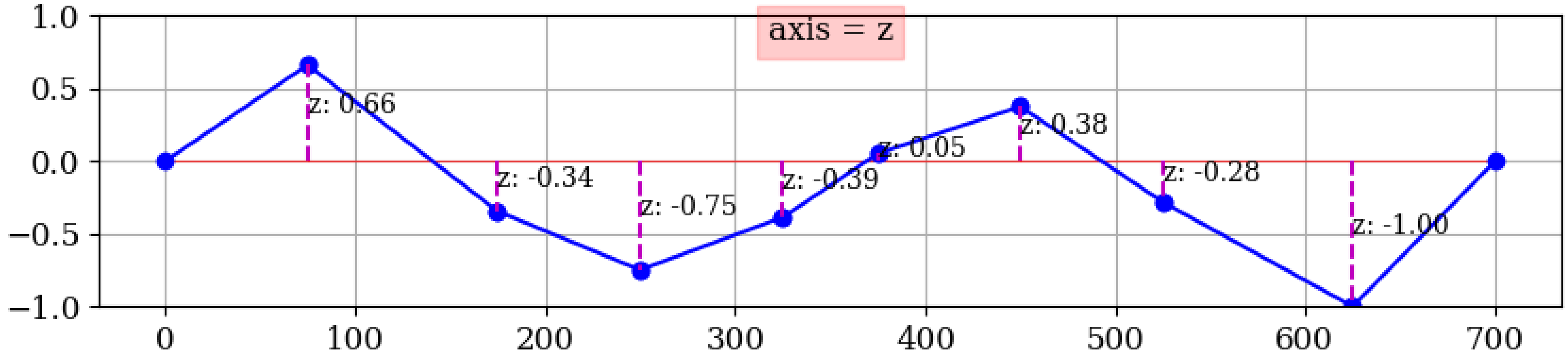


4^{th} Bending mode (69.00 Hz)

MEMS

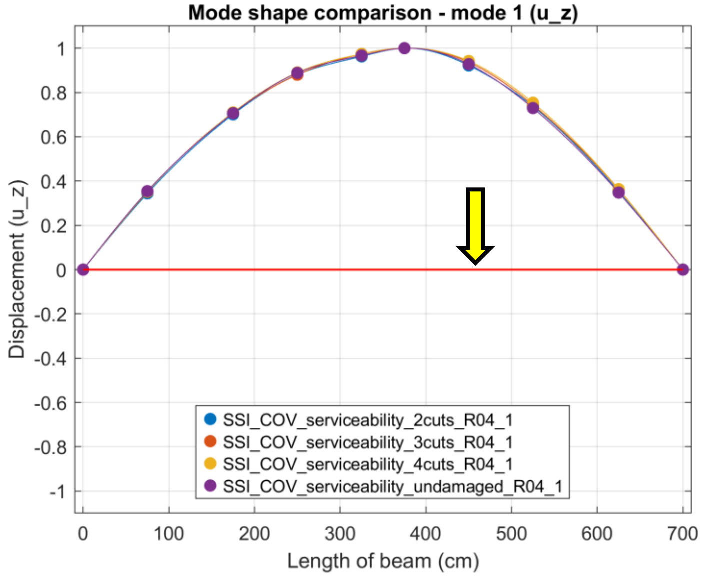


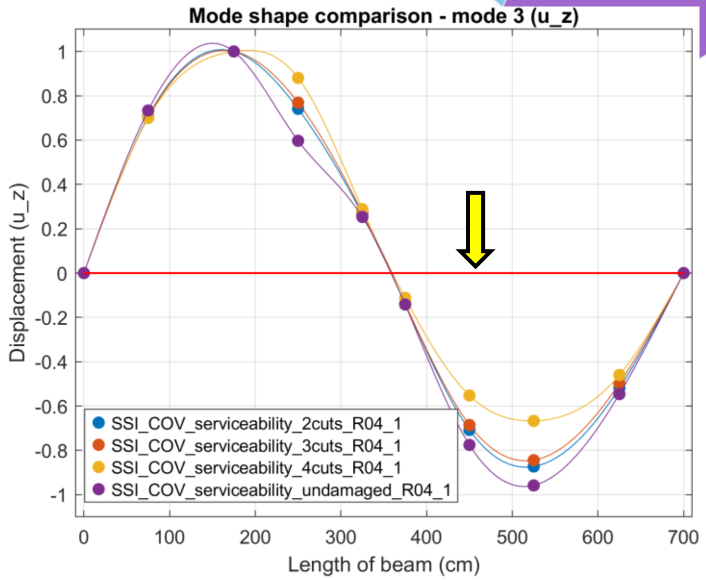
PCB

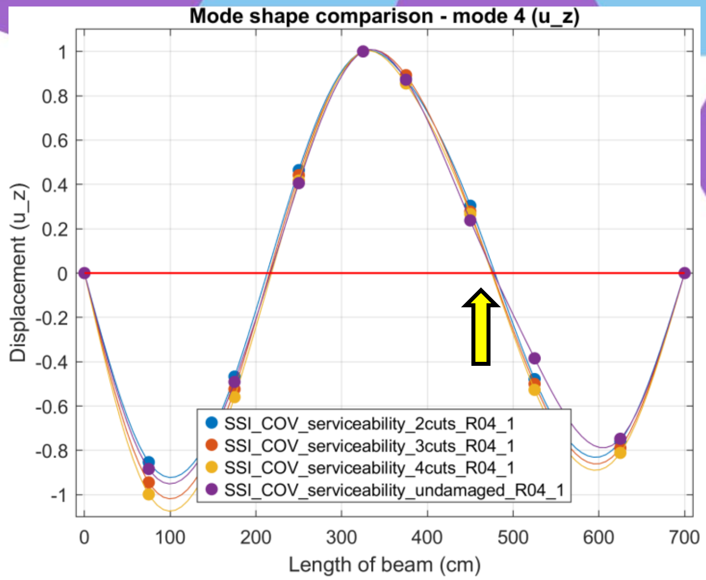


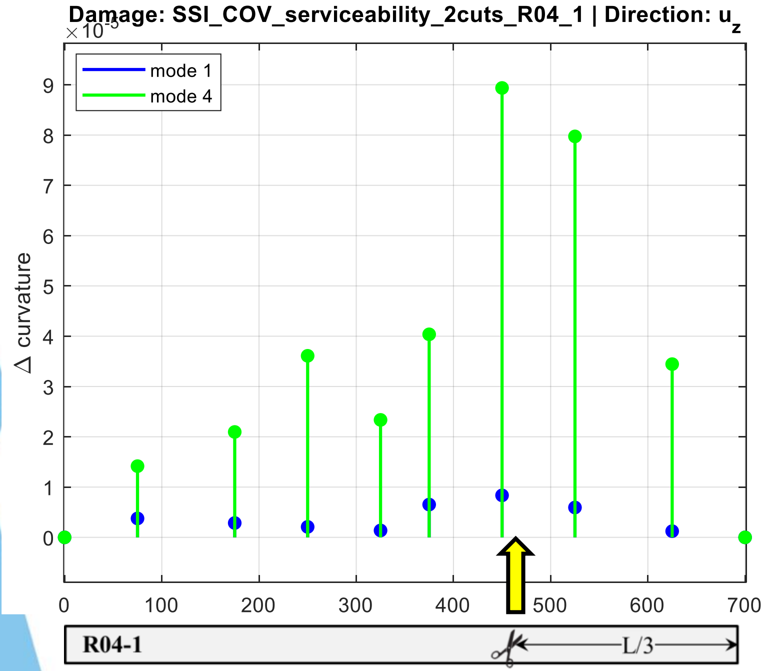
RESULTS AT SLS – MODAL CURVATURE COMPARISON

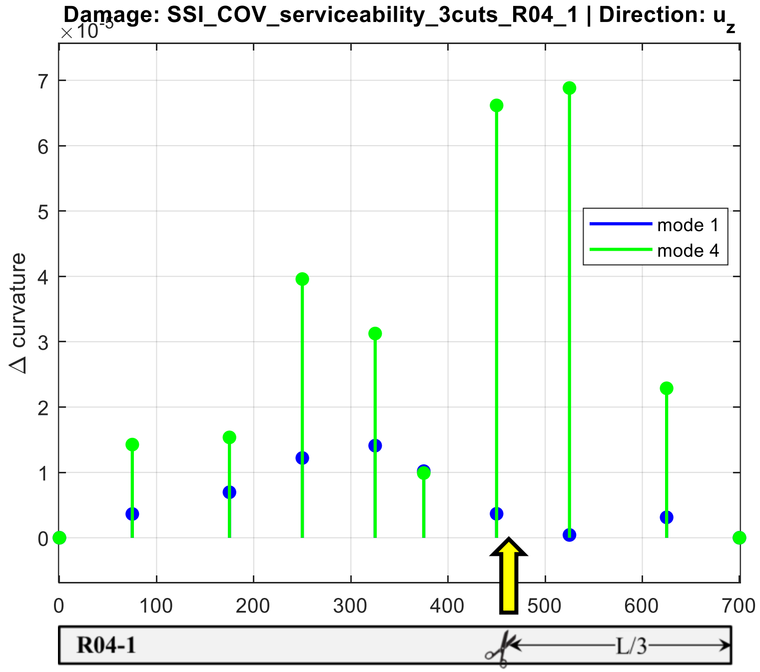
R04-1 L/3 = 466 cm L/3

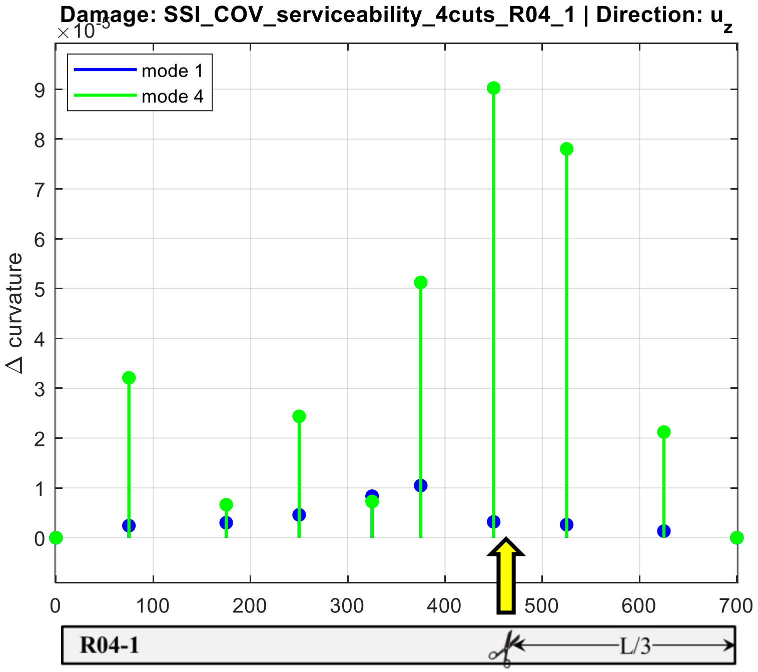




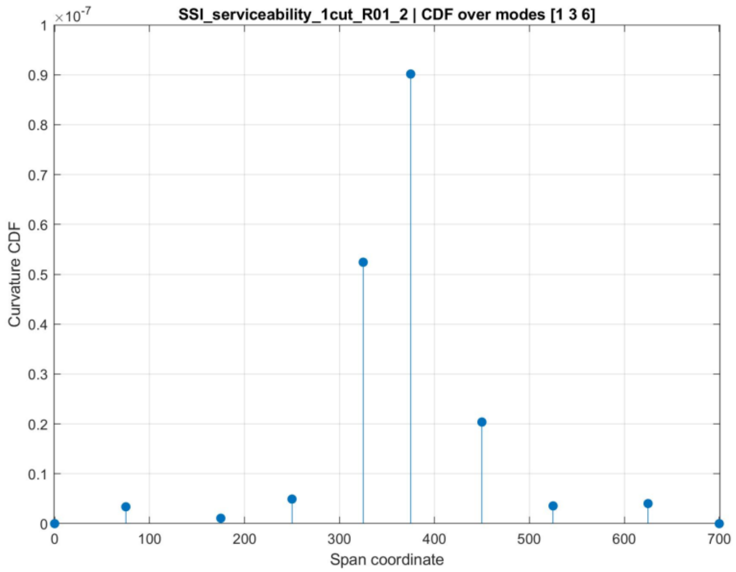


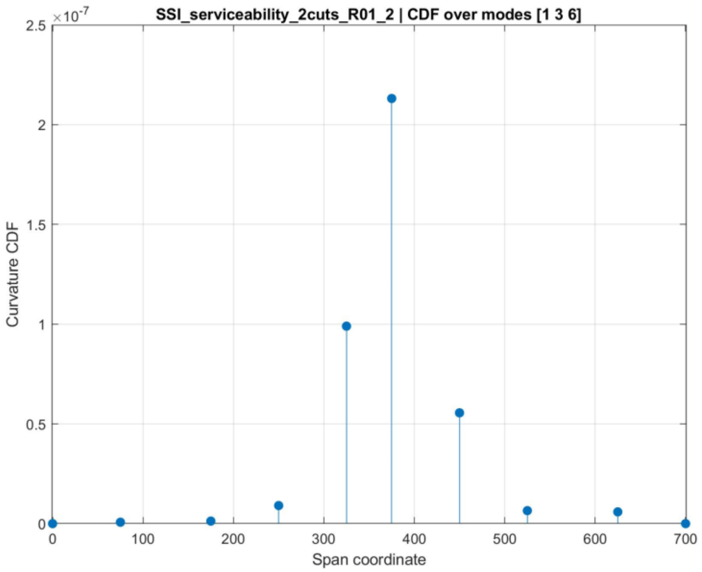


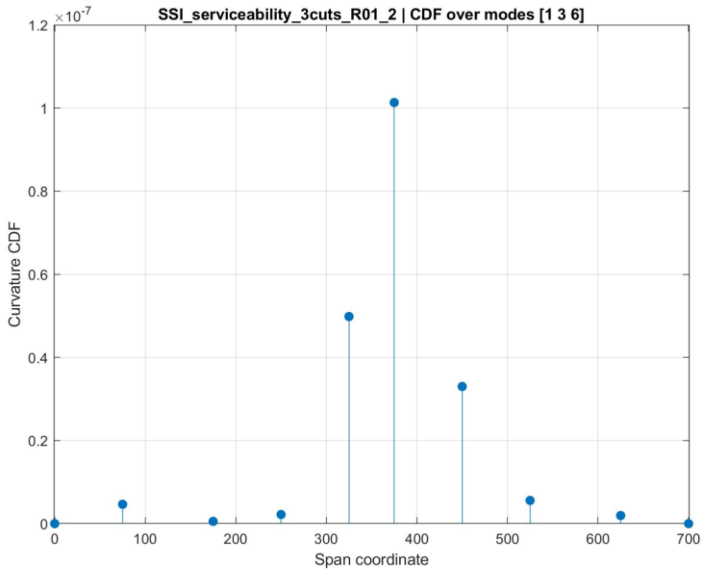


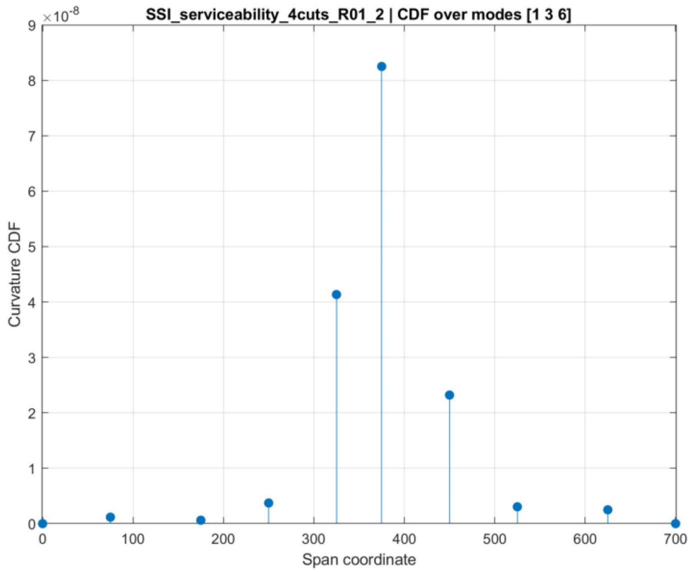


Bonded beam – Damage at L/2: Curvature CDF for bending modes

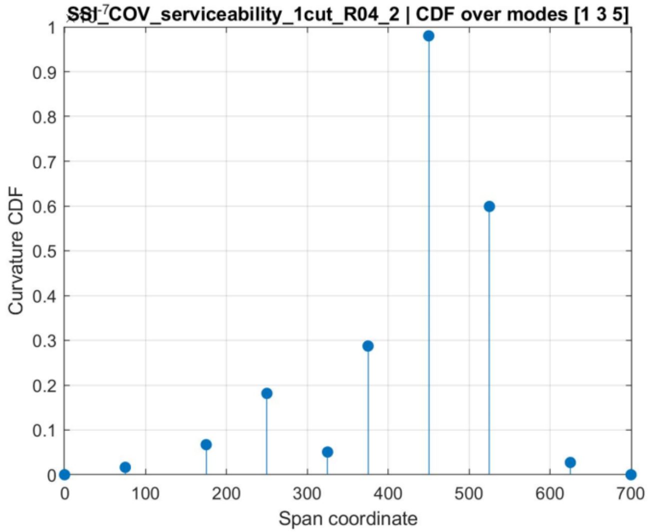


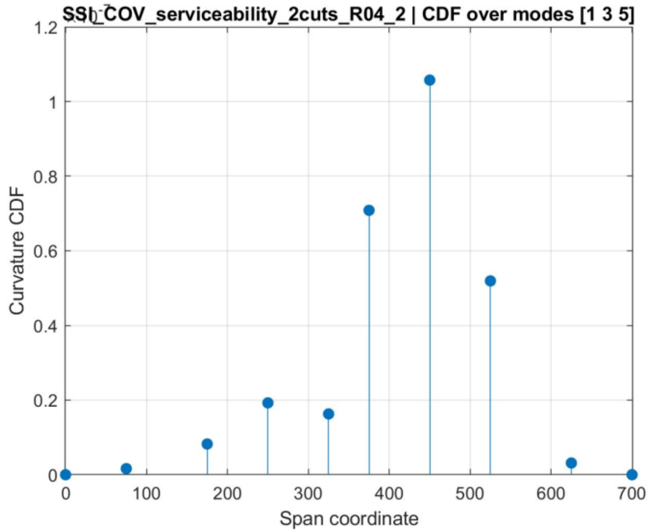


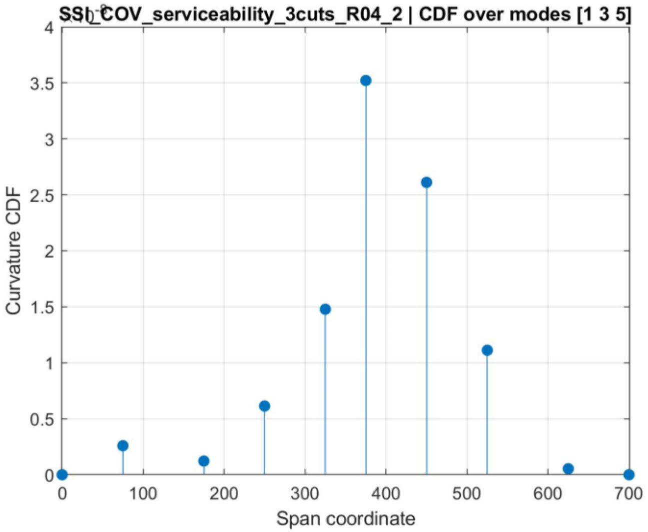


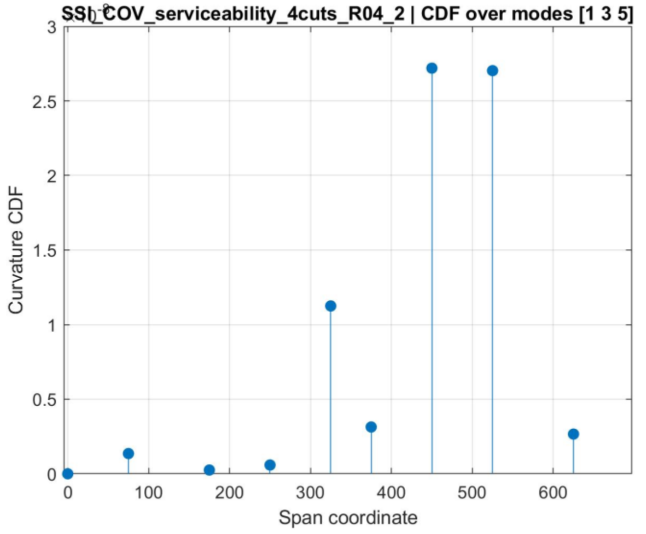


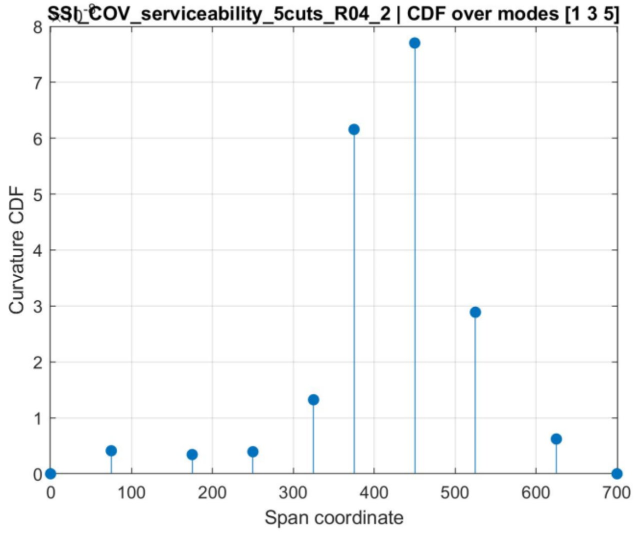
Bonded beam – Damage at L/3: Curvature CDF for bending modes

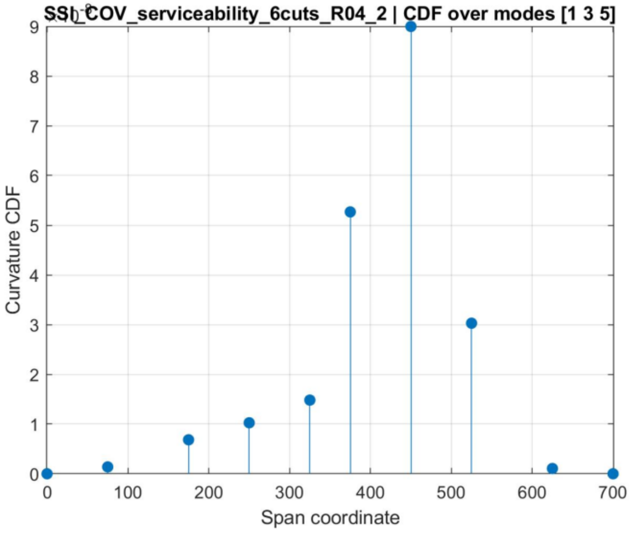




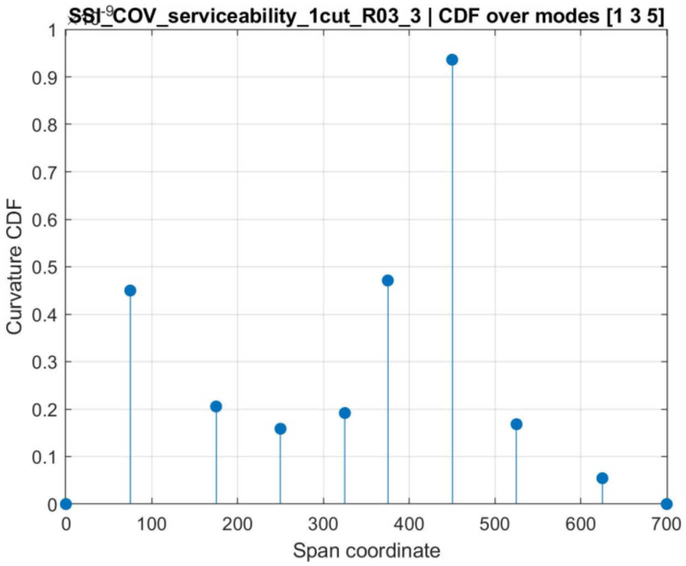


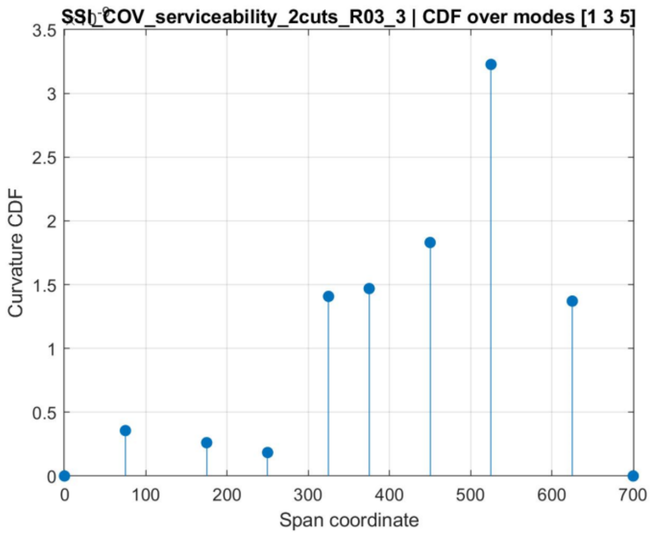


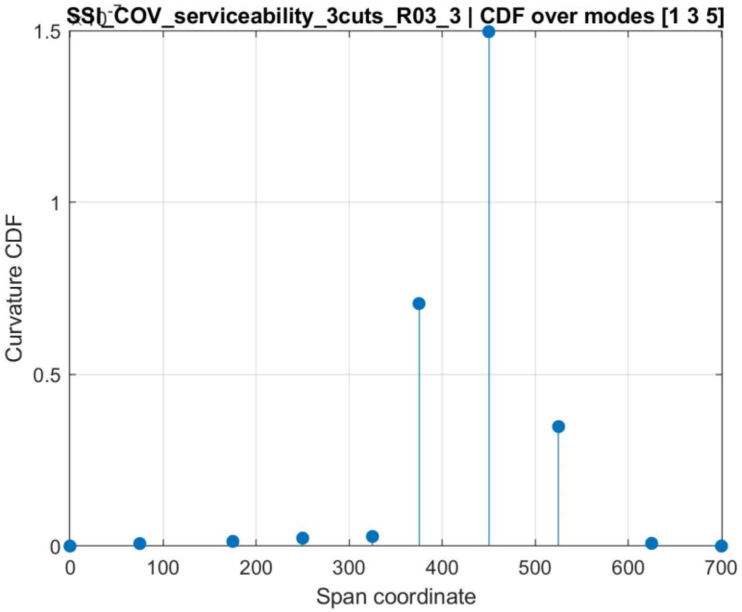


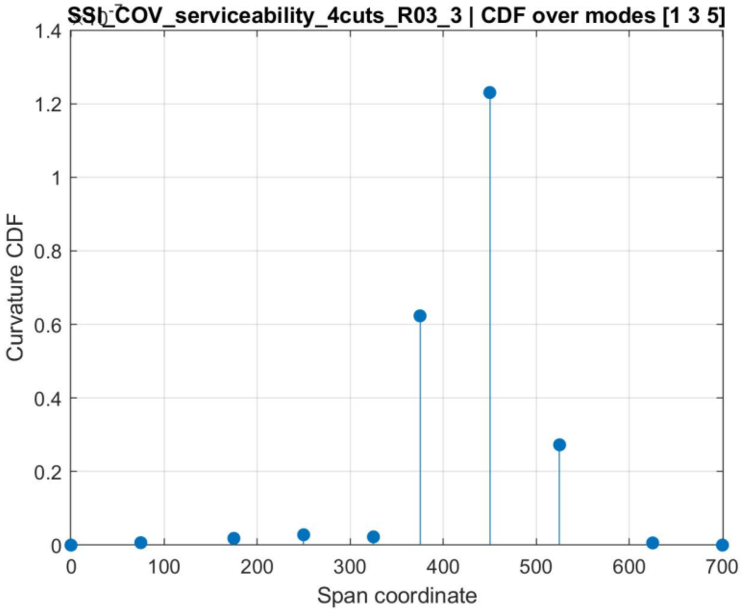


Bonded beam – Damage at L/4: Curvature CDF for bending modes

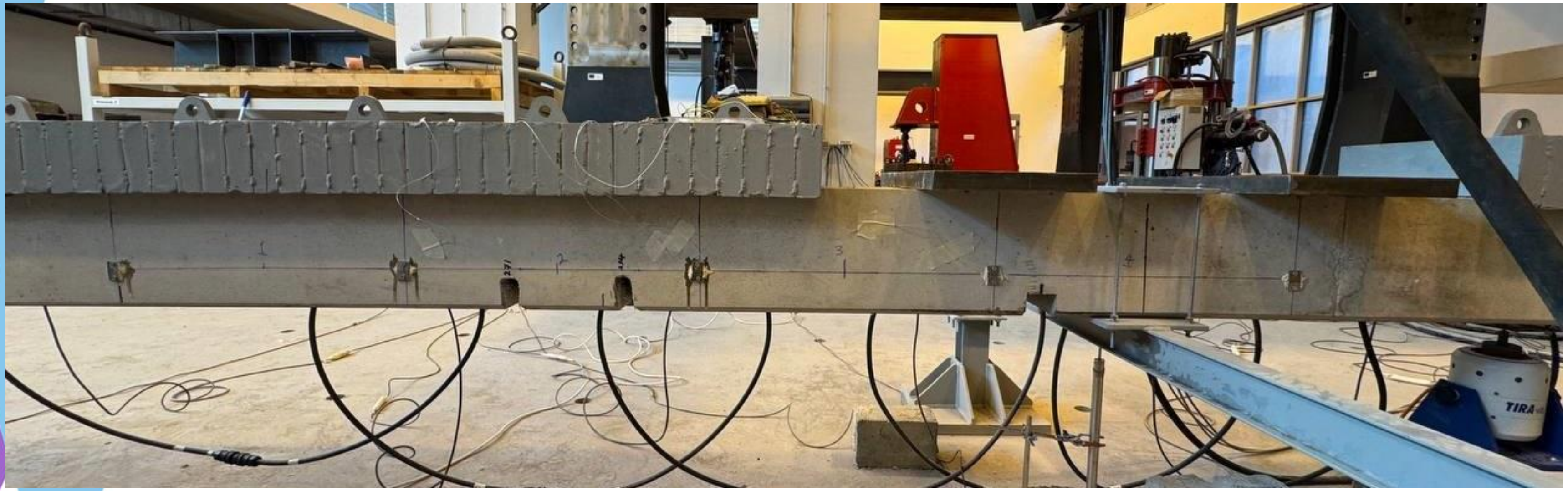


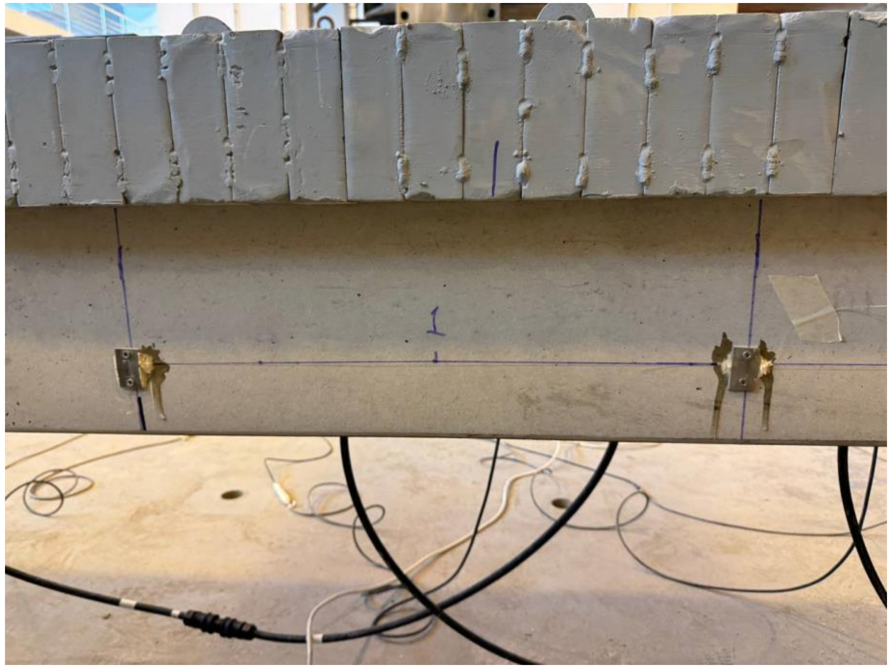






R04-3 : Damages in three inspection window

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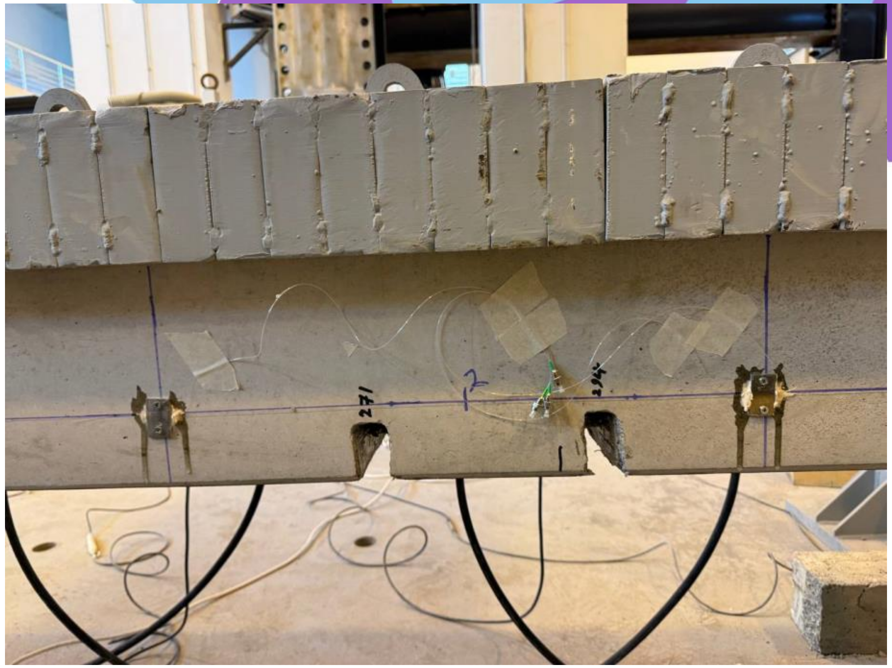
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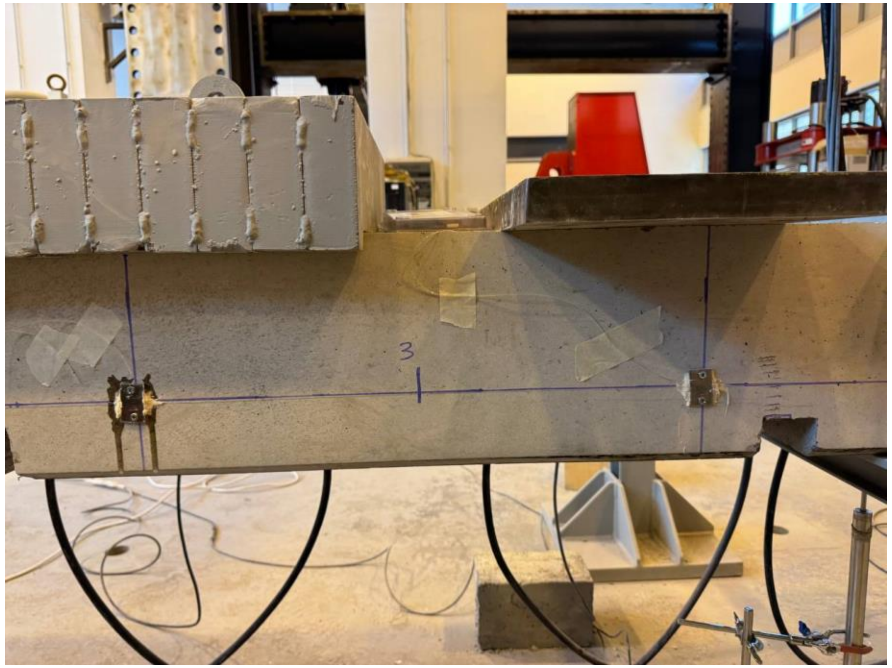
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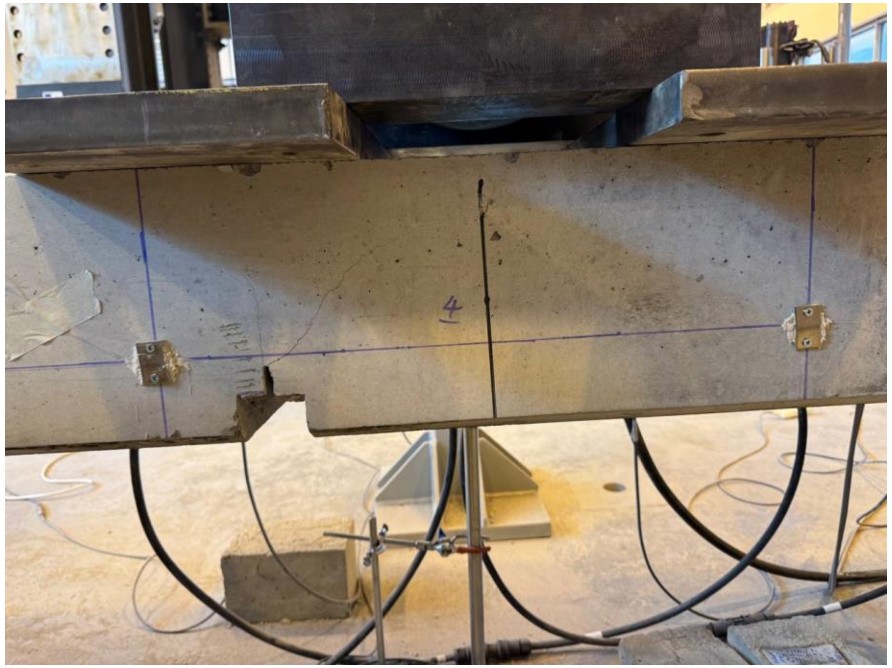
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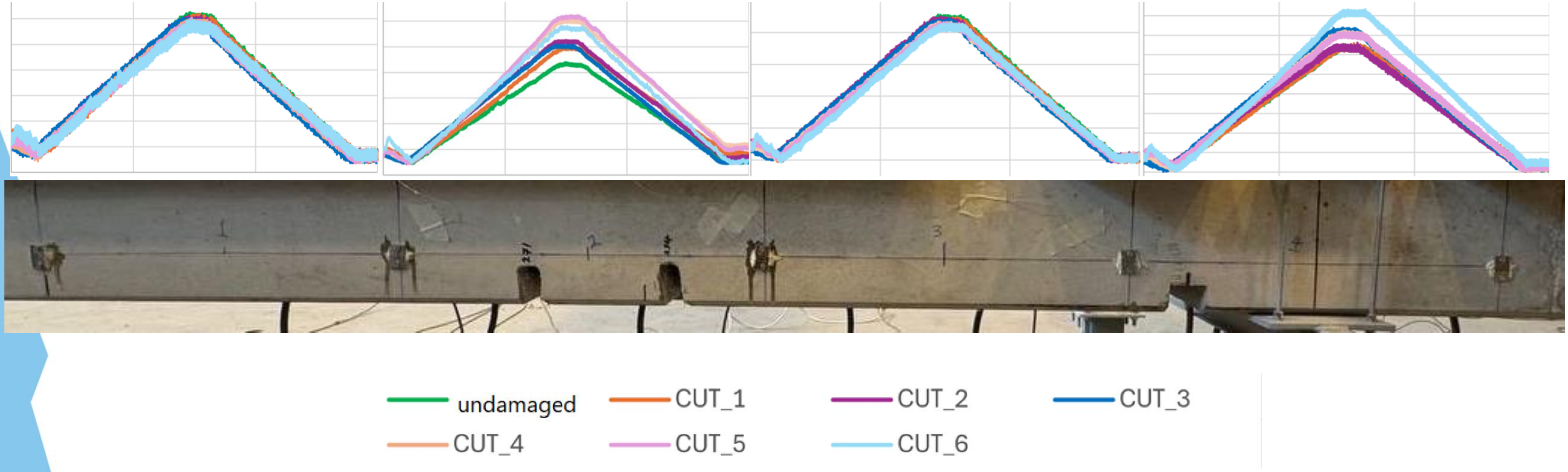
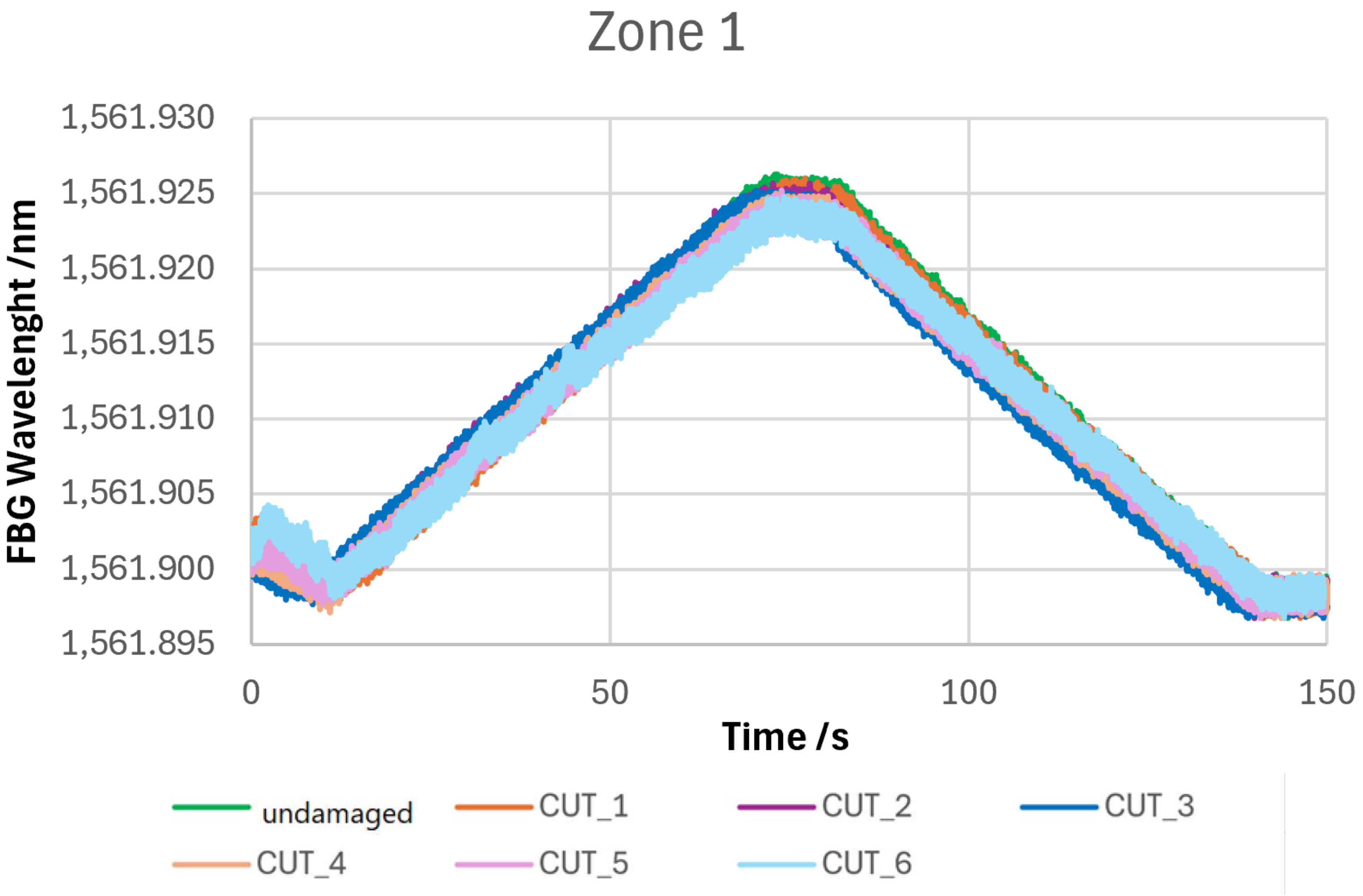
Serviceability _ loading unloading15kN_All zones



Serviceability _ loading unloading15kN



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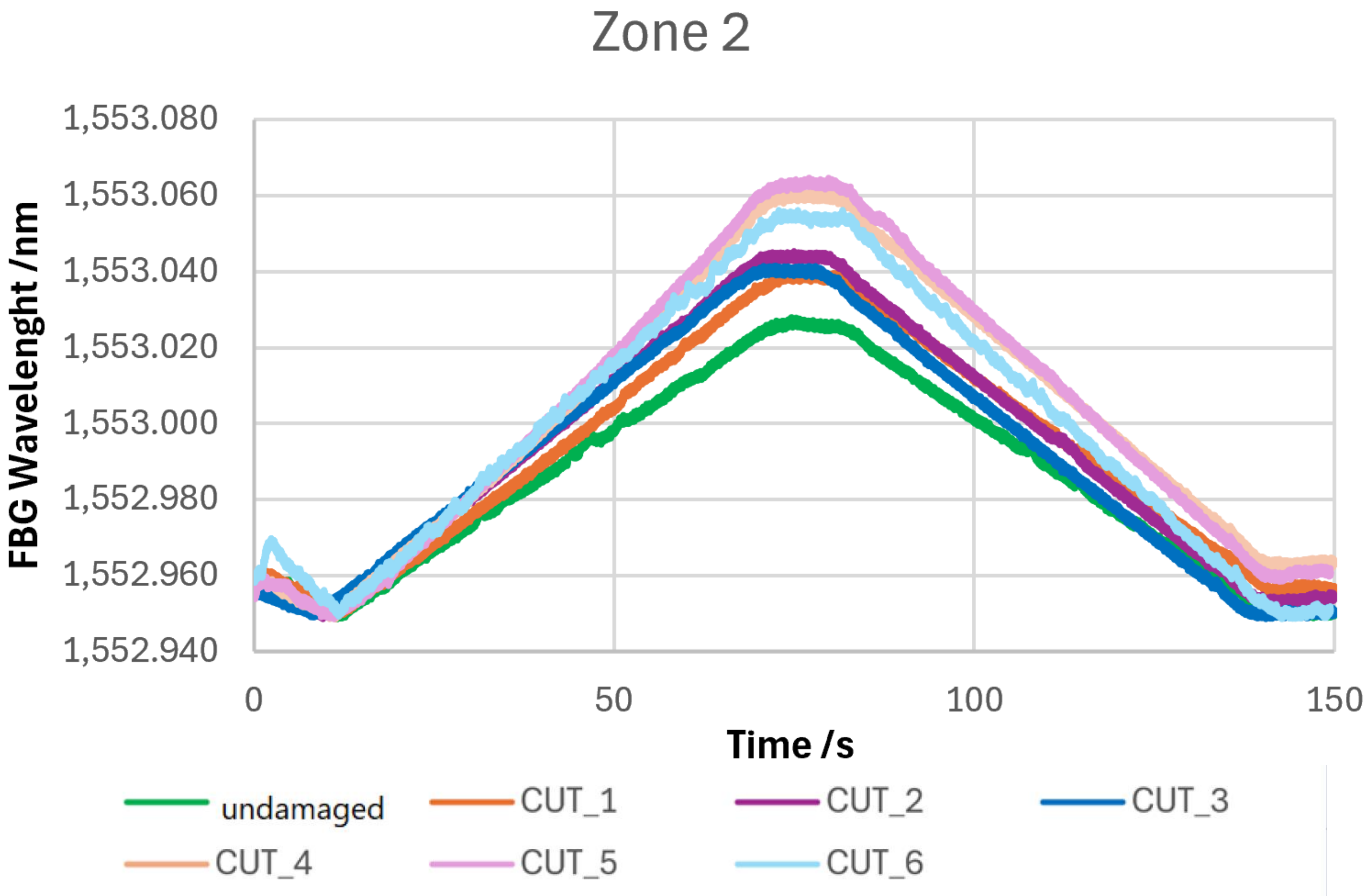

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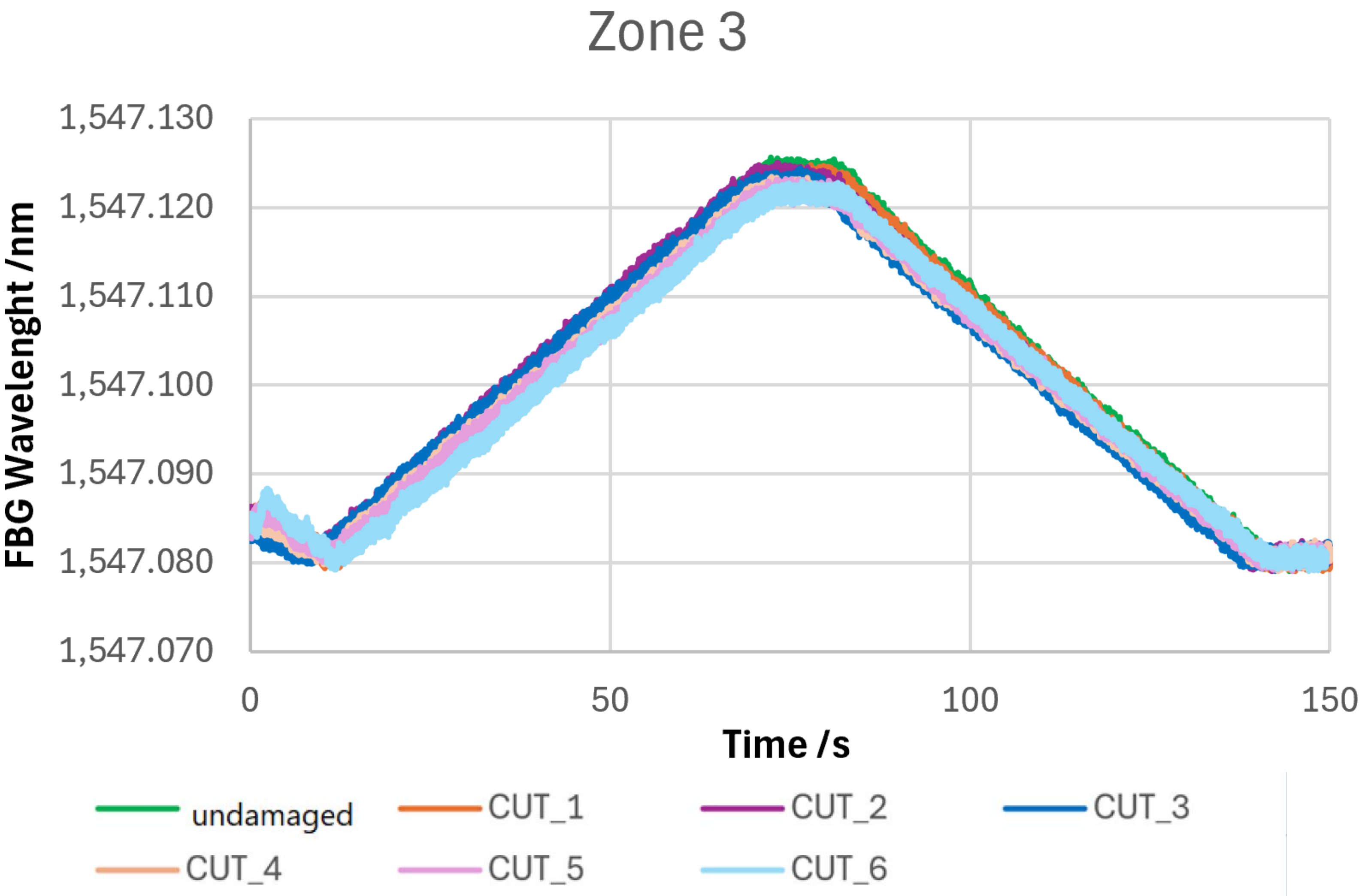

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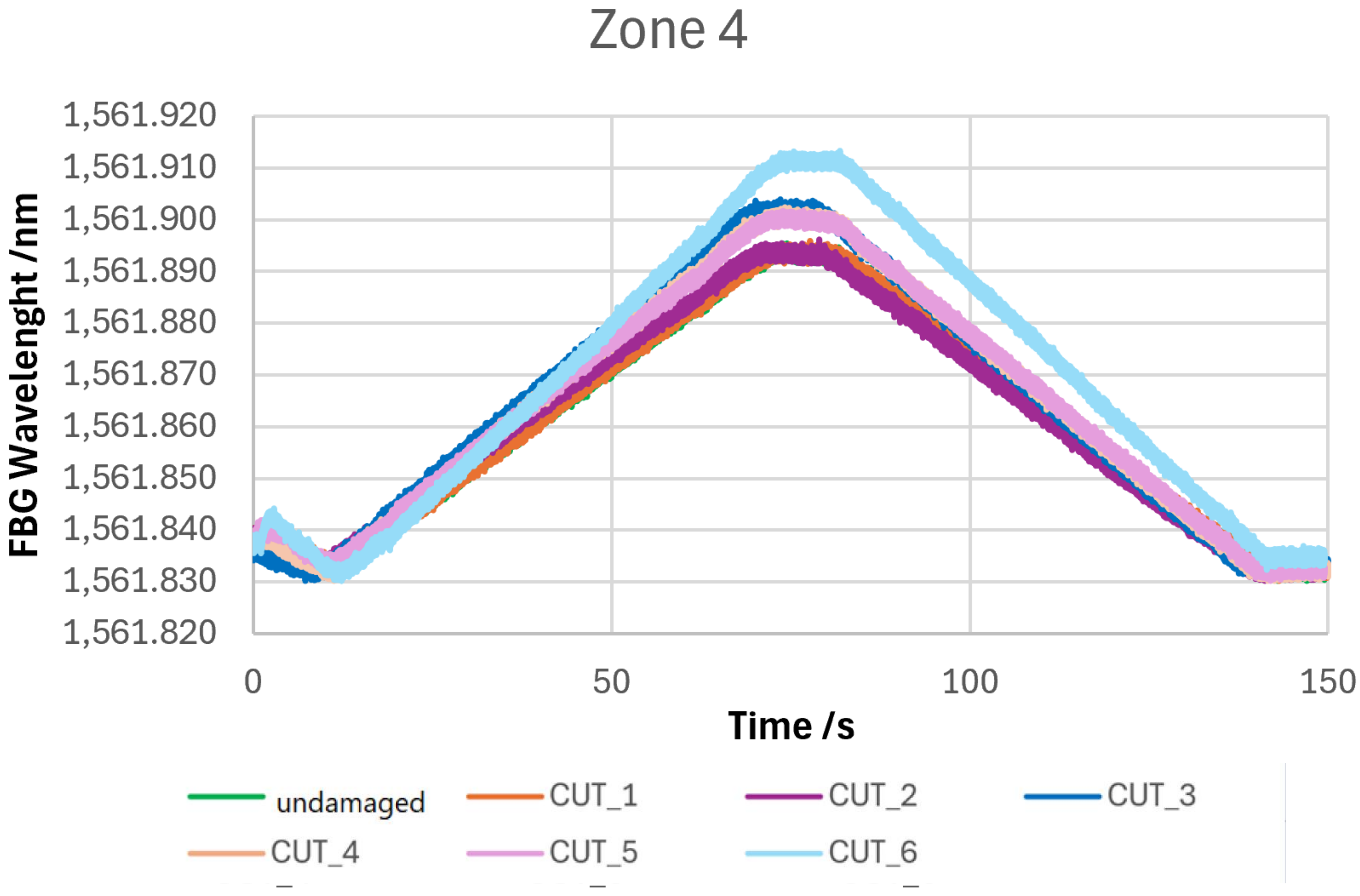

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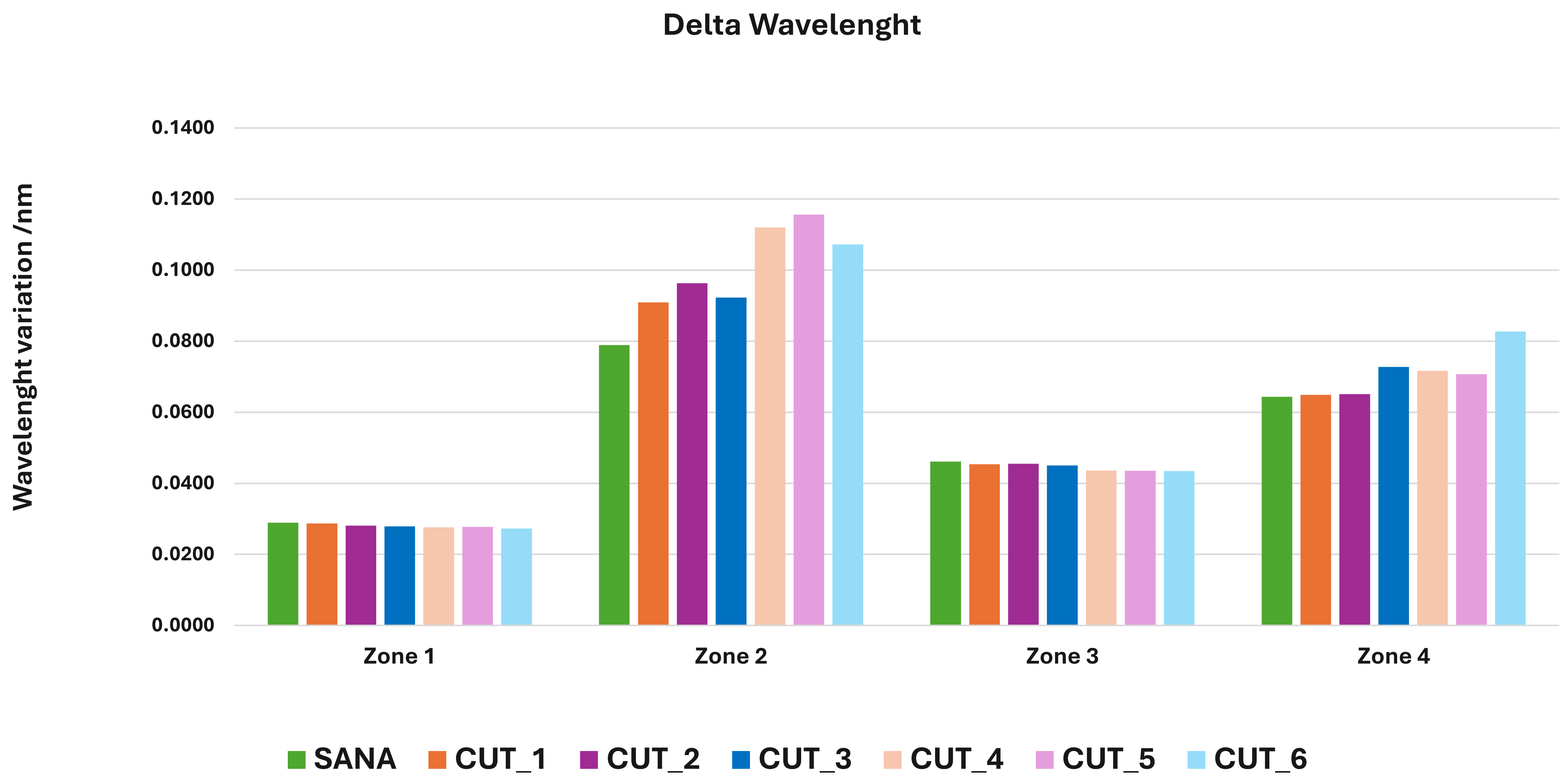

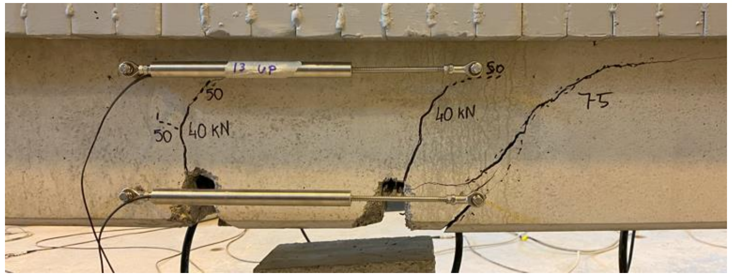

Università degli Studi di Messina
DIPARTIMENTO DI INGEGNERIA

THANK YOU FOR YOUR KIND ATTENTION

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