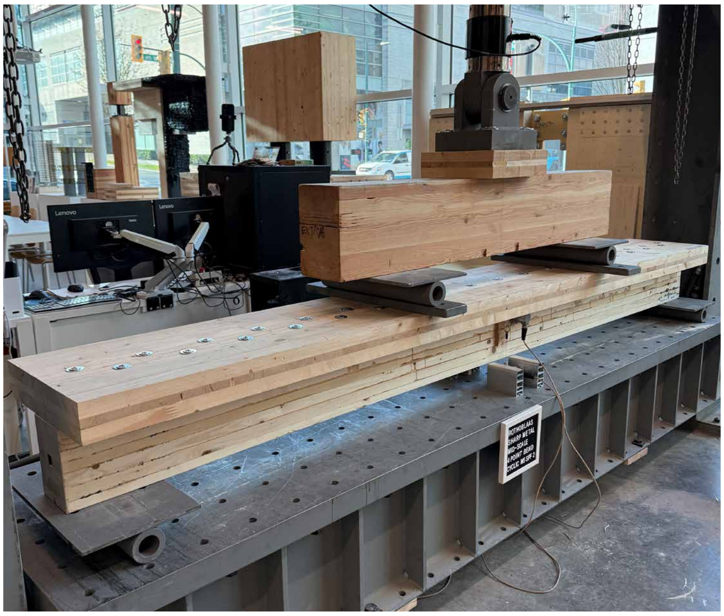
Comparative tests on connections for ribbed pannels

TECHNICAL REPORT



Solutions for Building Technology

SUMMARY

1. DESCRIPTION OF THE TEST CAMPAIGN

The experimental campaign was organized and planned to obtain a comprehensive overview of the behaviour of the connection made with SHARP METAL toothed plates. In particular, thanks to small-scale tests on the individual components, it was possible to model and predict the behaviour of larger specimens and verify the performance in full-scale elements. To accurately compare the theoretical results with the experimental ones, bending tests were carried out on the individual timber components (glulam beams, GL, and cross-laminated timber, CLT panels).

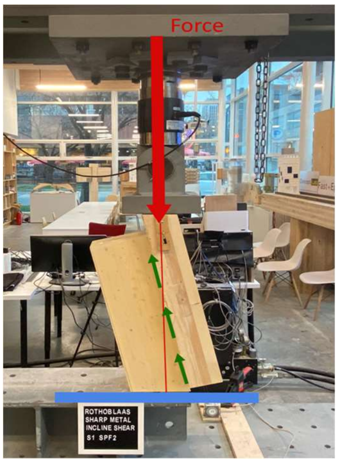
1.1. Phase 1 – Small scale inclined shear tests

The first part of the test campaign focused on the in-plane shear transfer between the CLT and glulam specimens. The geometry of the timber elements was consistent across all tests and consisted of samples measuring 130 mm wide GL and 265 wide CLT and 600 mm in length for both CLT and glulam members. The test setup was designed as an inclined shear configuration following EN 408, with loading applied at approximately 15° of inclination. The four-test series are:

- S1: CLT joined to GL with 90° screws only for 3 trials with Euro spruce, 3 trials with SPF
- S2: CLT joined to GL with the same 90° screws as S1, plus Sharp Metal centred on the board face 6 trials with Euro spruce, 6 trials with SPF
- S3: CLT joined to GL with the same 90° screws as S1, plus Sharp Metal on the lamination joint for 6 trials with SPF
- S4: CLT joined to GL with the same 90° screws as S1, plus glue 3 trials with Euro spruce.

The washer head timber Screws (TBSMAX 8mm) provide the clamping force both for SHARP METAL plates and for the glue joint. The objective of the S1 test series is to evaluate the mechanical behaviour of a ductile connection made with screws under identical boundary conditions (material, geometry, and test setup). This series represents the lower bound of stiffness and bearing strength in the initial portion of the load–displacement curve. The upper bound of stiffness and load-carrying capacity is determined through the S4 test series, in which the stiffest configuration is assessed by means of glue-bonded components. Test series S2 and S3 investigate the behaviour of SHARP METAL connectors under varying geometries and materials. In these configurations, the hooked plates are embedded into the timber members through screw pressing.

(a)



(b)

Picture 1: (a) Smal scale specimens. (b) load distribution.

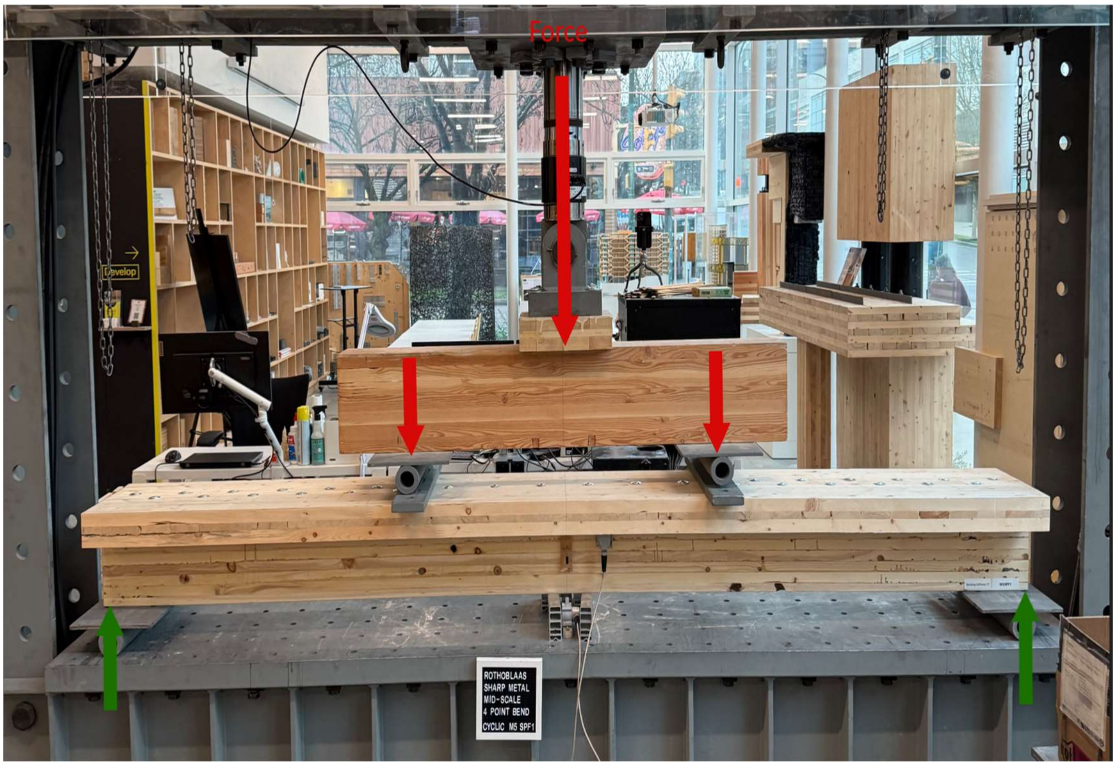
1.2. Phase 2 – Mid - scale four point bending tests – destructive

The full-scale (mid-scale) testing campaign was planned to verify the behaviour of the connections previously tested at small scale, applying them to a complete structural element such as a ribbed floor system. For this purpose, 3-m-long specimens were assembled, consisting of beams and panels made of both European and North American timber. The sizes of the elements are: GL 135×190 mm and CLT panels 105x400 mm, composed of 3 ply for North American timber and 140×200 mm and CLT panels 90×400 mm, composed of 3 ply for European timber:

The test setup consists of a four-points bending configuration. The tests included in this series are the same as in the small-scale tests:

- CLT joined to GL with 90° screws only for 3 trials with Euro spruce
- CLT joined to GL with the same 90° screws as test 1, plus Sharp Metal centred on the board face for 3 trials with Euro spruce, 3 trials with SPF
- CLT joined to GL with the same 90° screws as test 1, plus Sharp Metal on the lamination joint for3 trials with SPF
- CLT joined to GL with the same 90° screws as test 1, plus glue 3 trials with Euro spruce

In addition to the previous series, non-destructive tests were carried out on the individual components to determine their elastic bending stiffness.



Picture 2: Mid-scale test specimens-load distribution and test setup.

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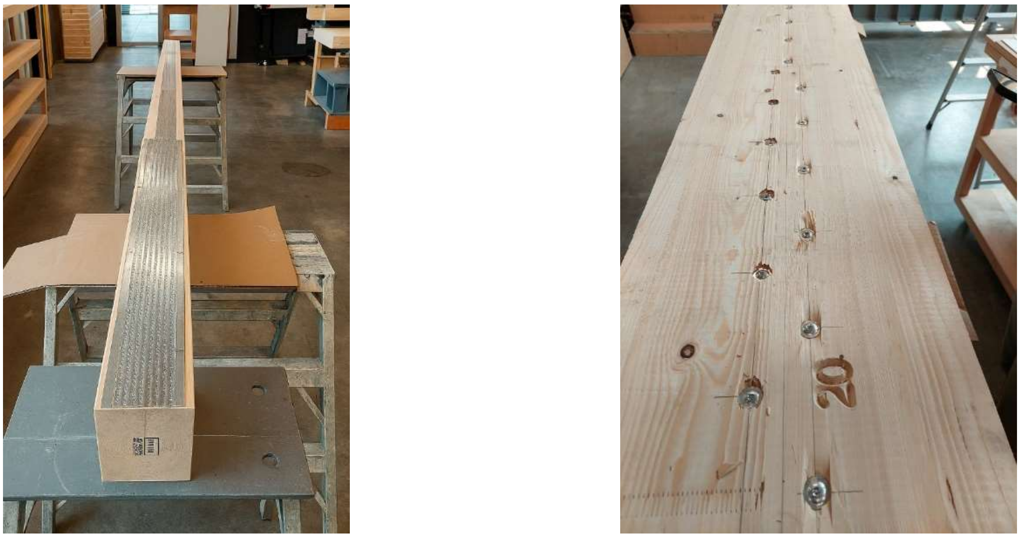
The arrangement of the connections between the CLT panels and the beams follows an optimization pattern based on the maximum shear force corresponding to the expected maximum slip. The layout foresees two connection strips at the supports, covering approximately one third of the span, and one strip in the middle, where the slip is zero.



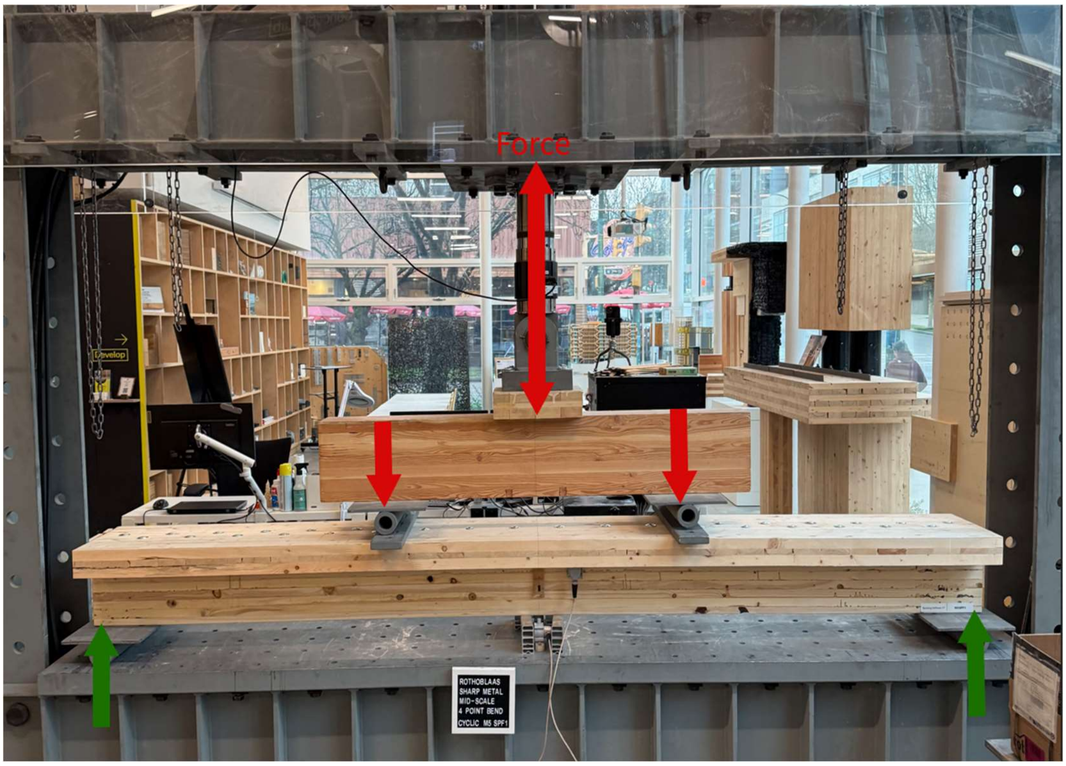
(a) (b)

Picture 3: Mid scale testing - (a) SHARP METAL plates and (b) TBSmax screws

1.3. Phase 3 – Mid - scale four point bending tests – cyclic

The third step of the testing program is the verification of the results through a cyclic loading protocol. The floor specimens from Phase 2 were tested by alternating loading cycles with increasing amplitudes and unloading cycles back to zero displacement (the initial reference point). This testing procedure aims to assess the degradation of the connection up to failure. The Series 3 test program consists of the following tests:

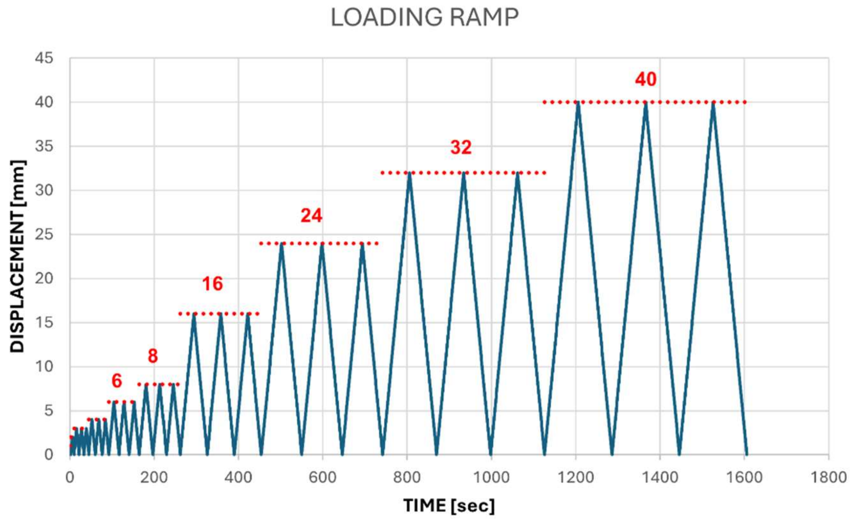
- CLT joined to glulam with 90-degree screws plus Sharp Metal centred on the board face for 3 trials with Euro spruce, 3 trials with SPF



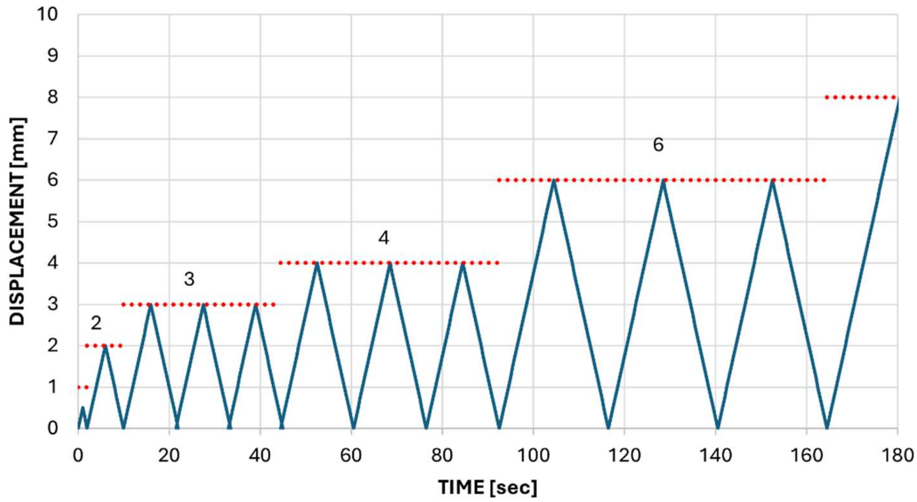
Picture 4: Mid-scale test specimens-load distribution and test setup.

n° of cycles [–]	% υ_y [–]	υ [mm]	Corresponding deflection limit L/xx [-]	Fv monotonic test [kN]	Notes
1	0,25	1	3000	7	
1	0,50	2	1500	18	
3	0,75	3	1000	30	
3	1,00	4	750	35	
3	1,50	6	500	50	additional cycles - not included in EN12512
3	2,00	8	375	65	displacement level approximately corresponding to SLS
3	4,00	16	188	108	
3	6,00	24	125	140	additional cycles - not included in EN12512
3	8,00	32	94	140	Possible failure at the first cycle
3	10,00	40	75	140	Probable failure at the first cycle - not included in EN12512

Table 1:Cyclic test protocol



(a)



(b)

Picture 5: Cyclic test protocol (a) cycles (b) zoom of the first part of the protocol.

1.4. Phase 3 – Creep tests (on-going)

The same test set up and connection options will be tested again with a sustained load equal to 30-40% of the average load value determined from the Phase 2 tests. The specimens will be loaded, and the force will be sustained for a period of 6 months.

- CLT joined to glulam with 90-degree screws plus Sharp Metal centred on the board face - 2 trials with Euro spruce and 2 trials with SPF.

2. SMALL SCALE INCLINED SHEAR TESTS -RESULTS

S1 = CLT and GL joined only with 90° screws

Name	TIMBER	TYPE/GRADE CLT	TYPE/GRADE GL	CLT DENSITY [kg/m³]	GL DENSITY [kg/m³]	CONNECTION
S1_EU_1	EU	C24 3 PLY 30/30/30	GL24h	466	398	3 TBS MAX 8x240
S1_EU_2				452	386	
S1_EU_3				431	398	
S1_SPF_1	NA	No2 & btr	No2 & btr	472	538	3 TBS MAX 8x240
S1_SPF_2				449	531	
S1_SPF_3				478	538	

S2 = CLT and GL joined only with 90° screws and SHARP METAL

Name	TIMBER	TYPE/GRADE CLT	TYPE/GRADE GL	CLT DENSITY [kg/m³]	GL DENSITY [kg/m³]	CONNECTION
S2_EU_1	EU	C24 3 PLY 30/30/30	GL24h	410	538	3 TBS MAX 8x240 + 50 x 480mm section of SHARP501200
S2_EU_2				438	545	
S2_EU_3				483	538	
S2_EU_4				449	538	
S2_EU_5				455	517	
S2_EU_6				472	538	
S2 SPF_1	NA	No2 & btr 3 PL 35/35/35	No2 & btr	410	538	3 TBS MAX 8x240 + 50 x 480mm section of SHARP501200
S2 SPF_2				438	545	
S2_SPF_3				483	538	
S2_SPF_4				449	538	
S2_SPF_5				455	517	
S2_SPF_6				472	538	

S3 = CLT with lamination joint and GL joined with 90° screws and SHARP METAL

Name	TIMBER	TYPE/GRADE CLT	TYPE/GRADE GL	CLT DENSITY [kg/m³]	GL DENSITY [kg/m³]	CONNECTION
S3_SPF_1	NA	No2 & btr 3 PL 35/35/35	No2 & btr	455	510	3 TBS MAX 8x240 + 50 x 480mm section of SHARP501200
S3_SPF_2				449	538	
S3_SPF_3				449	559	
S3_SPF_4				438	538	
S3_SPF_5				466	538	
S3_SPF_6				461	538	

S4 = CLT joined to GL with the same 90° screws as S1 and glue

Name	TIMBER	TYPE/GRADE CLT	TYPE/GRADE GL	CLT DENSITY [kg/m³]	GL DENSITY [kg/m³]	CONNECTION
S4_EU_1	EU	C24 3 PLY 30/30/30	GL24h	445	410	3 TBS MAX 8x240 + POLIURETANIC ALIFATIC RESIN
S4_EU_2				445	404	
S4_EU_3				445	381	

Table 2:Small scale test geometry, samples composition and test results.

S1 = CLT and GL joined only with 90° screws

Name S1	F_{max} [kN]	V_{max} [mm]	F_{0-15} [kN]	V_{0-15} [mm]	F_{15} [kN]	V_{15} [mm]	F_{01} [kN]	v_{01} [mm]	F_{04} [kN]	v_{04} [mm]	K_s [N/mm]	Failure mode
EU_1	51,1	71,6	-	-	16,0	15	1,6	2,0	6,4	4,2	2182	15mm displacement conventional failure
EU_2	53,2	78,8			19,1		1,9	0,8	7,6	3,3	2292	
EU_3	62,5	74,1			22,1		2,2	0,7	8,8	3,6	2286	
SPF_1	61,4	69,2	-	-	25,5	15	2,6	0,1	10,2	1,4	5885	15mm displacement conventional failure
SPF_2	53,2	67,2			24,5		2,5	0,06	9,8	1,1	6806	
SPF_3	53,4	67,6			23,0		2,3	0,06	9,2	1,3	5743	

S2 = CLT and GL joined only with 90° screws and SHARP METAL

Name	F_{max}	V_{max}	F_{0-15}	V_{0-15}	F_{15}	V_{15}	F_{01}	v_{01}	F_{04}	v_{04}	K_s	Failure
S2	[kN]	[mm]	[kN]	[mm]	[kN]	[mm]	[kN]	[mm]	[kN]	[mm]	[N/mm]	mode
EU_1	59,0	77,5	37,0	11,5	31,4		3,1	0,027	12,6	0,4	26744	
EU_2	59,3	46,8	42,6	11,2	41,8		4,2	0,07	16,7	0,8	16724	
EU_3	62,9	65	39,92	12,4	39,1	15	3,9	0,08	15,7	0,5	28639	15mm displacement conventional failure
EU_4	62,5	70,6	39,6	10,1	38,8		3,9	0,11	15,5	0,8	17898	
EU_5	59,4	76,0	-	-	37,7		3,8	0,05	15,1	0,8	15493	
EU_6	67,2	72,3	38,8	12,0	38,2		3,8	0,11	15,3	0,6	22453	
SPF_1	82,3	87,4	40,8	4,0	37,0		3,7	0	14,8	0,2	69717	
SPF_2	83,2	84,3	54,1	3,4	45,1		4,5	0,03	18,0	0,2	67643	
SPF_3	99,9	75,2	46,1	4,8	57,4	15	5,7	0,06	22,9	0,3	78232	15mm displacement conventional failure
SPF_4	99,9	70,6	57,3	4,5	51,3		5,1	0,10	20,5	0,4	59135	
SPF_5	112,7	87,0	52,0	4,7	56,4		5,6	0,09	22,6	0,5	47013	
SPF_6	102,5	86,5	47,7	3,6	47,4		4,7	0,09	18,9	0,4	54640	

S3 = CLT with lamination joint and GL joined only with 90° screws and SHARP METAL

Name	F_{max}	V_{max}	F_{0-15}	V_{0-15}	F_{15}	V_{15}	F_{01}	v_{01}	F_{04}	v_{04}	K_s	Failure
S3	[kN]	[mm]	[kN]	[mm]	[kN]	[mm]	[kN]	[mm]	[kN]	[mm]	[N/mm]	mode
SPF_1	79,4	69,9	51,0	3,9	43,5		4,3	0,1	17,4	0,2	118582	
SPF_2	91,9	79,6	44,0	4,0	41,1		4,1	0,01	16,4	0,3	47406	
SPF_3	76,1	83,2	37,0	3,3	37,6	15	3,8	0,07	15,1	0,6	23522	15mm displacement conventional failure
SPF_4	87,7	85,7	57,3	3,3	41,0		4,1	0,03	16,4	0,2	61448	
SPF_5	111,4	87,0	41,9	6,6	40,5		4,1	0,07	16,2	0,4	36841	
SPF_6	104,9	86,2	45,0	5,4	45,1		4,5	0,09	18,0	0,5	35569	

S4 = CLT joined to GL with the same 90° screws as S1, plus glue

Name	F_{max}	V_{max}	F_{0-15}	V_{0-15}	F_{15}	V_{15}	F_{01}	v_{01}	F_{04}	v_{04}	K_s	Failure
S4	[kN]	[mm]	[kN]	[mm]	[kN]	[mm]	[kN]	[mm]	[kN]	[mm]	[N/mm]	mode
EU_1	292,3	2,6					29,2	0,2	116,9	1,0	123171	
EU_2	280,0	2,7	-	-	-	-	28,0	0,3	112,0	0,9	145132	Brittle failure glued conn.
EU_3	250,9	2,6					25,1	0,3	100,4	0,9	119097	

Table 3:Small scale test geometry, samples composition and test results.

All the tests performed were conducted up to large displacement levels in order to assess the large-displacement behaviour of the more ductile systems (S1–S2–S3). However, the maximum displacement value considered in the evaluation of strength and stiffness is limited to 15 mm, in accordance with EN 26891. For completeness, the maximum strengths and displacement reached during the entire test (F_{max}, V_{max}) are reported in the tables and graphs. The design values, however, refer to:

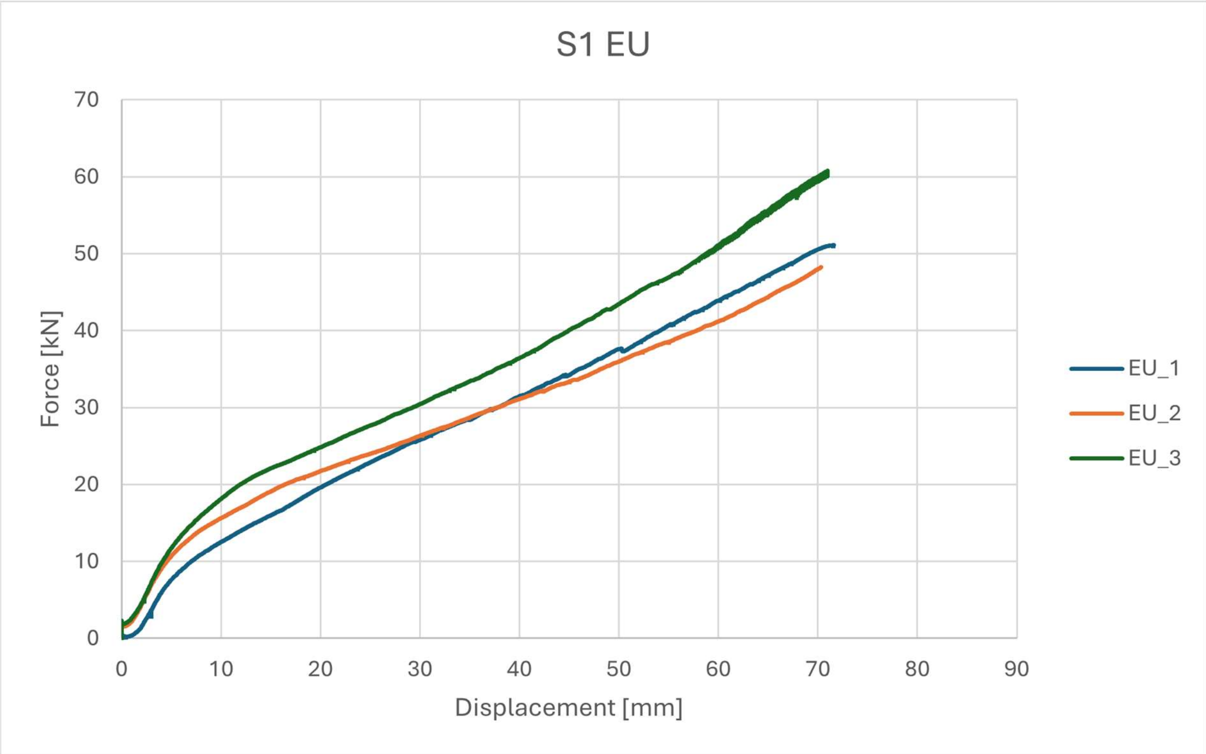
- $F_{0\text{-}15}$; $V_{0\text{-}15}$ peak value of force in the range 0-15mm - and corresponding displacement.
- F_{15} v_{15} peak value of force at conventional displacement 15mm.
- F_{01} v_{01} displacement corresponding to the level 10% of the load (Fmax or $F_{0\text{-}15}$ or F_{15})
- F_{04} v_{04} displacement corresponding to the level 40% of the load (Fmax or $F_{0\text{-}15}$ or F_{15})
- $_{ks}$ conventional stiffness secant between 10% and 40% of Fmax or $F_{0\text{-}15}$ or F_{15}

The behaviour of the screws in SPF timber is generally more consistent with analytical predictions and shows a significantly better performance compared to European wood, mainly due to its higher specific density (CLT-GL). The behaviour of the connection is consistent with indications found in the literature and exhibits a pseudo-plastic response up to large displacements. No unexpected failures occurred within the investigated range.

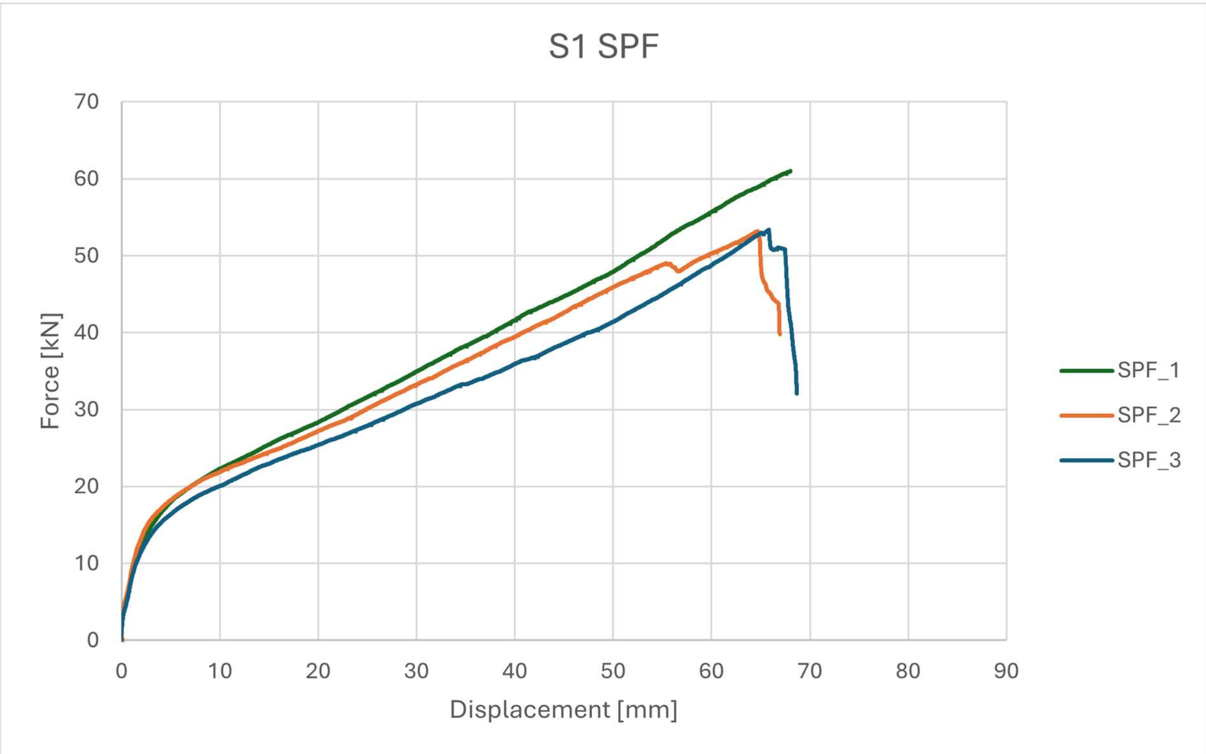
The recommendations for the characteristic design stiffness can be found in Eurocode 5 (EN 1995-1-1), although they retain a general and approximate nature that is acceptable only when stiffness is not the governing parameter in the design process.

	MEAN -EXP			K-FROM EXP		K-FROM DESIGN	
TEST	F_{15} [kN]	V_{15} [mm]	K_s [N/mm]	F_k [kN]	V_{15} [mm]	F_{15} [kN]	K_s [N/mm]
S1_EU	19	15	2253	11	15	14,6	8981
S1_SPF	24	15	6144	21	15	15,3	9795
S2_EU	39	15	21325	35	15	23,9	58045
S2_SPF	50	15	62730	37	15	25,6	58045
S3_SPF	46	15	53895	32	15	25,6	58045
S4_EU	274	2,7	129133	212	2,7	210	-

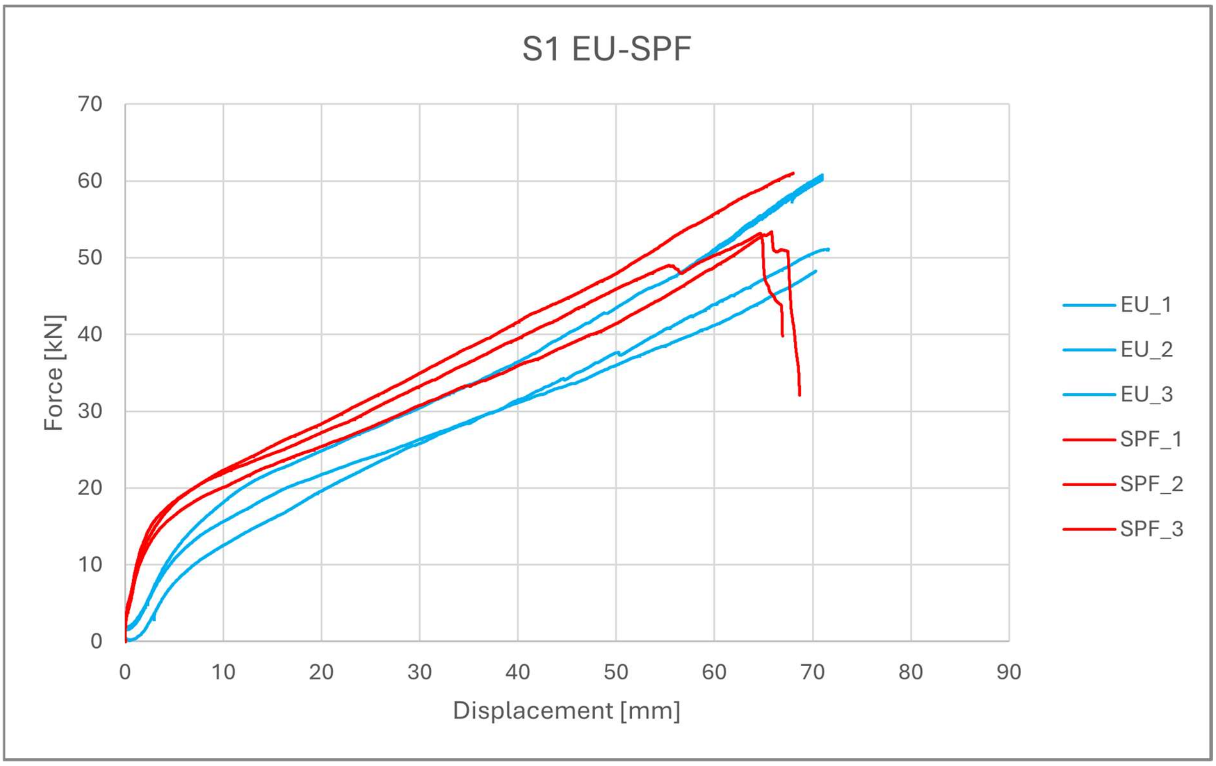
Table 4:Comparison between mean experimental values (Mean- Exp) and experimental characteristic values (K from EXP) and characteristc from analitical models (K from Design).



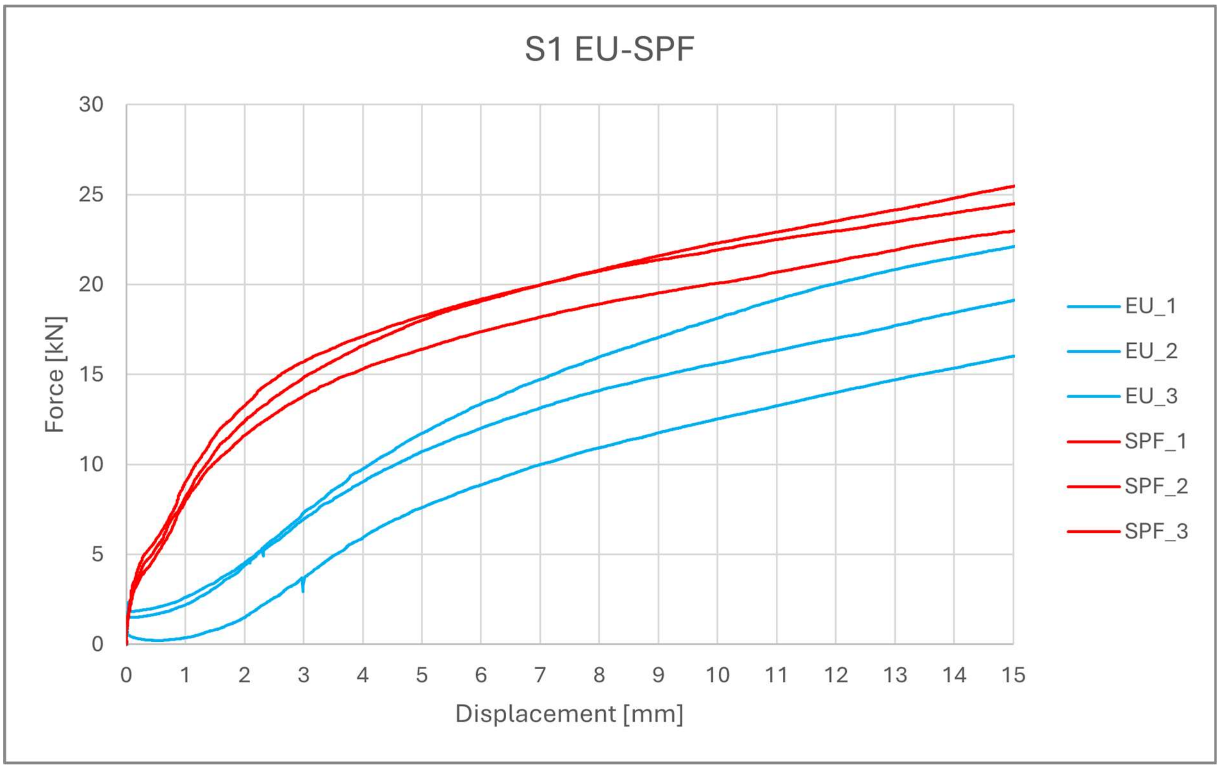
Picture 6:Test results S1 (screws) European Spruce



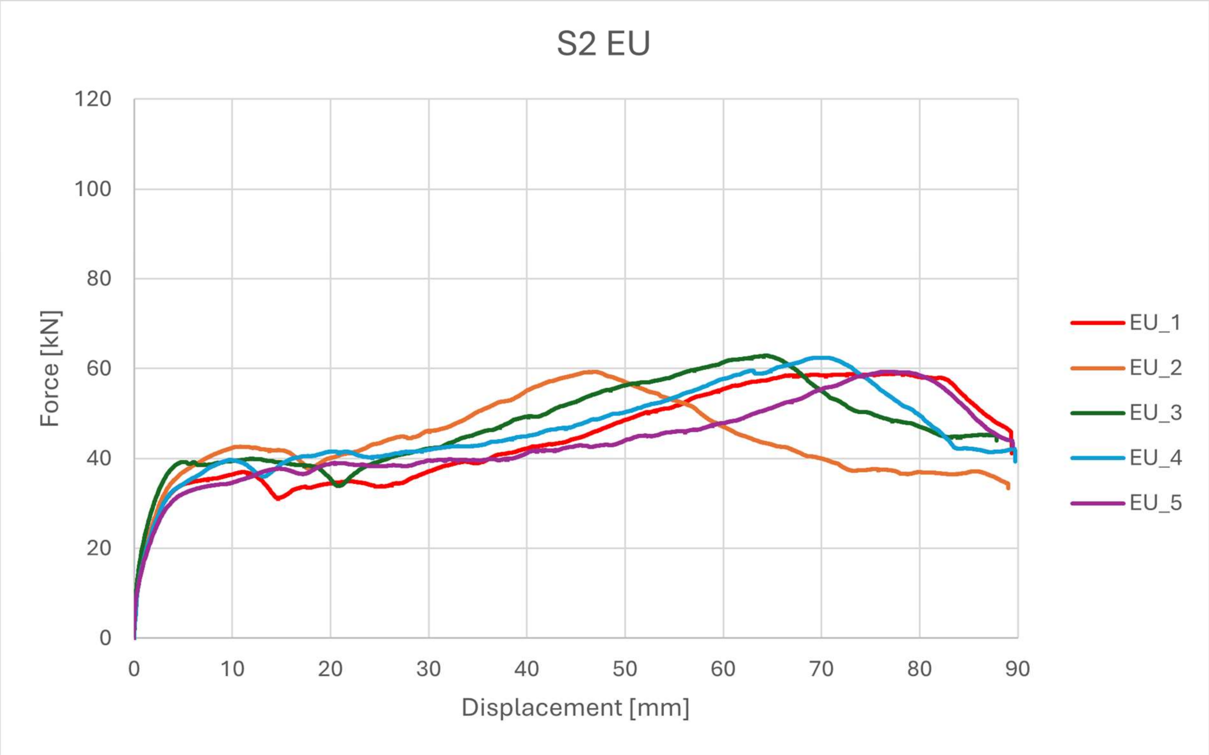
Picture 7:Test results S1 (screws) SPF.



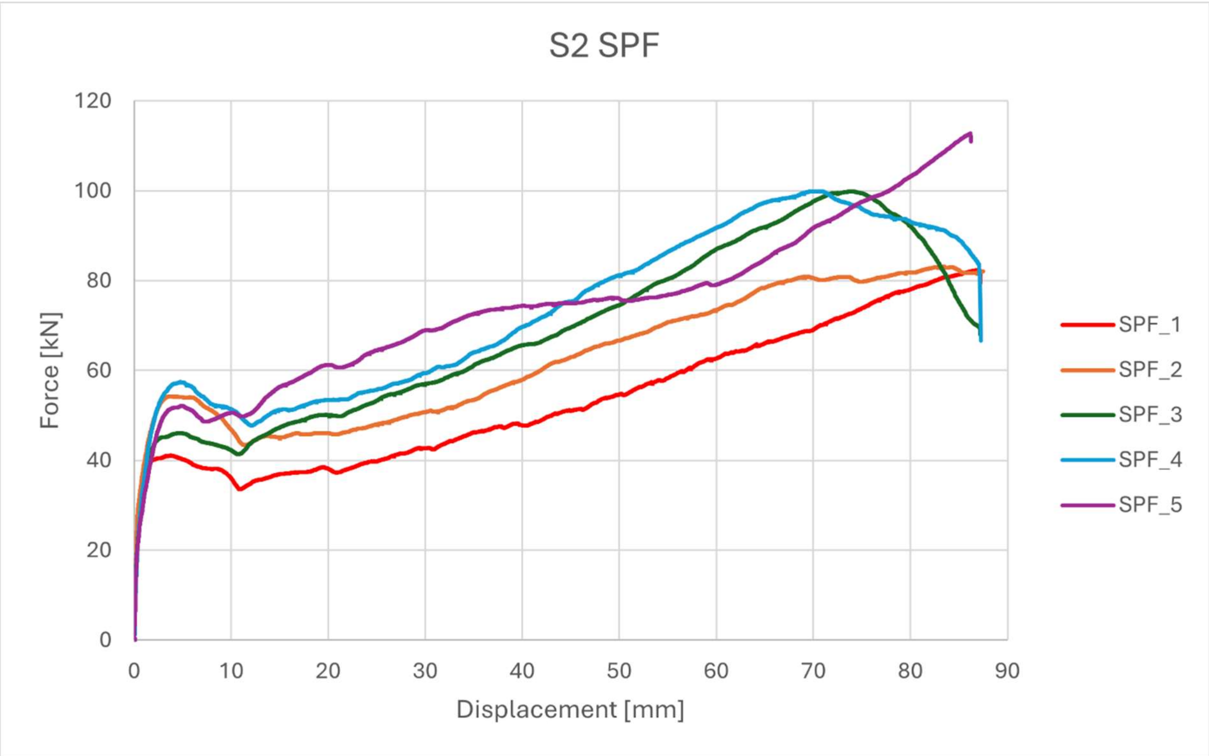
Picture 8: Comparison - test results S1 (screws) European and North American timber.



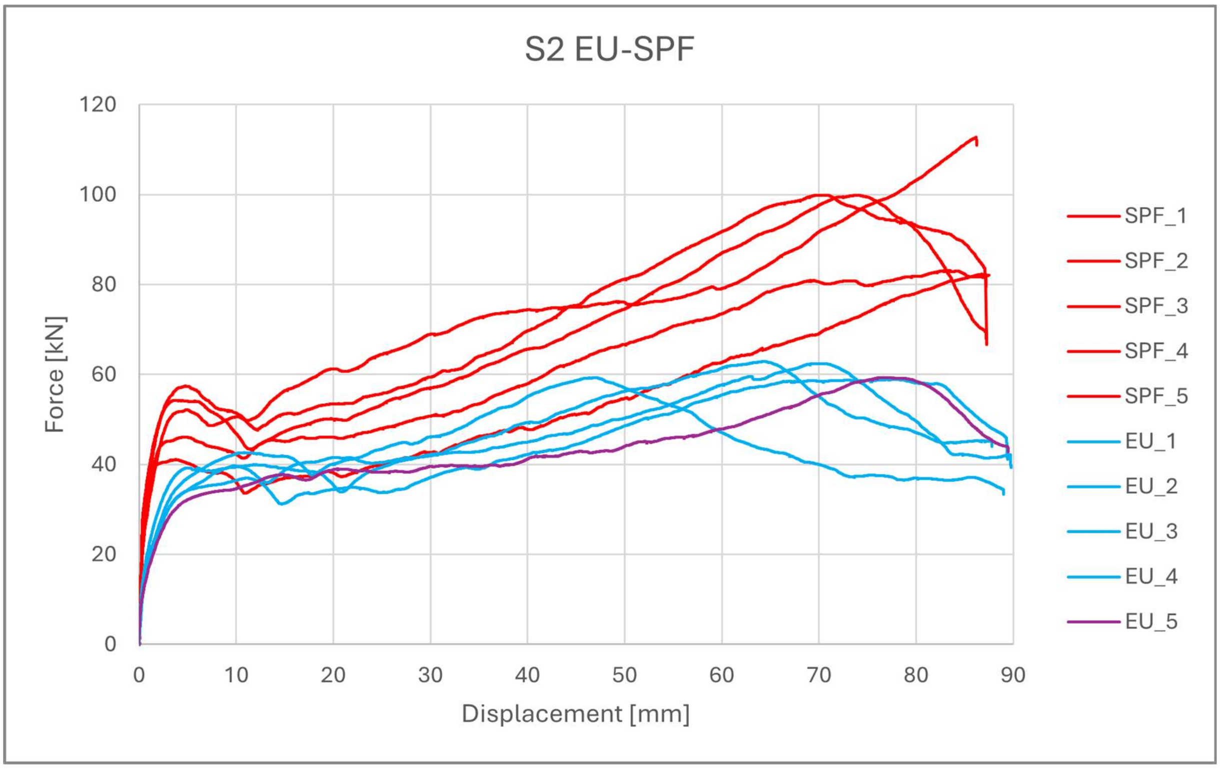
Picture 9:Comparison - test results S1(screws) zoom to 15mm.



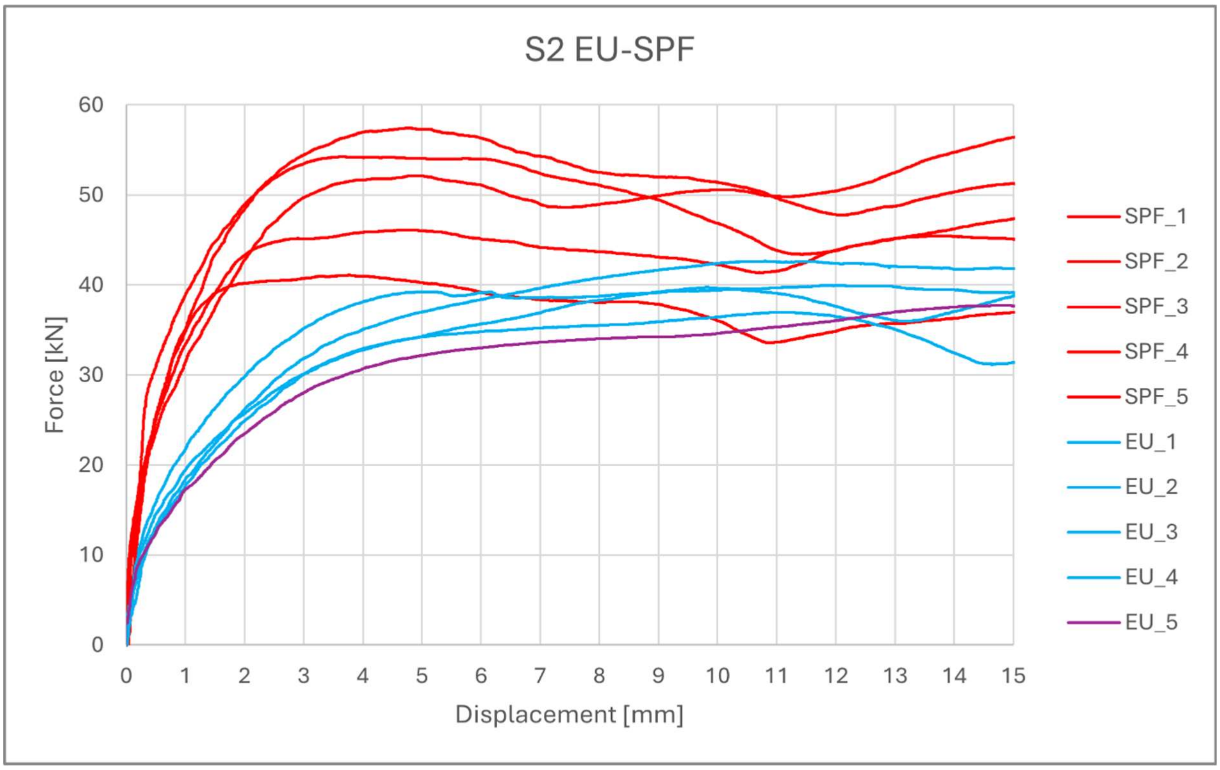
Picture 10: Test results S2 (screws + SHARP METAL) European Spruce



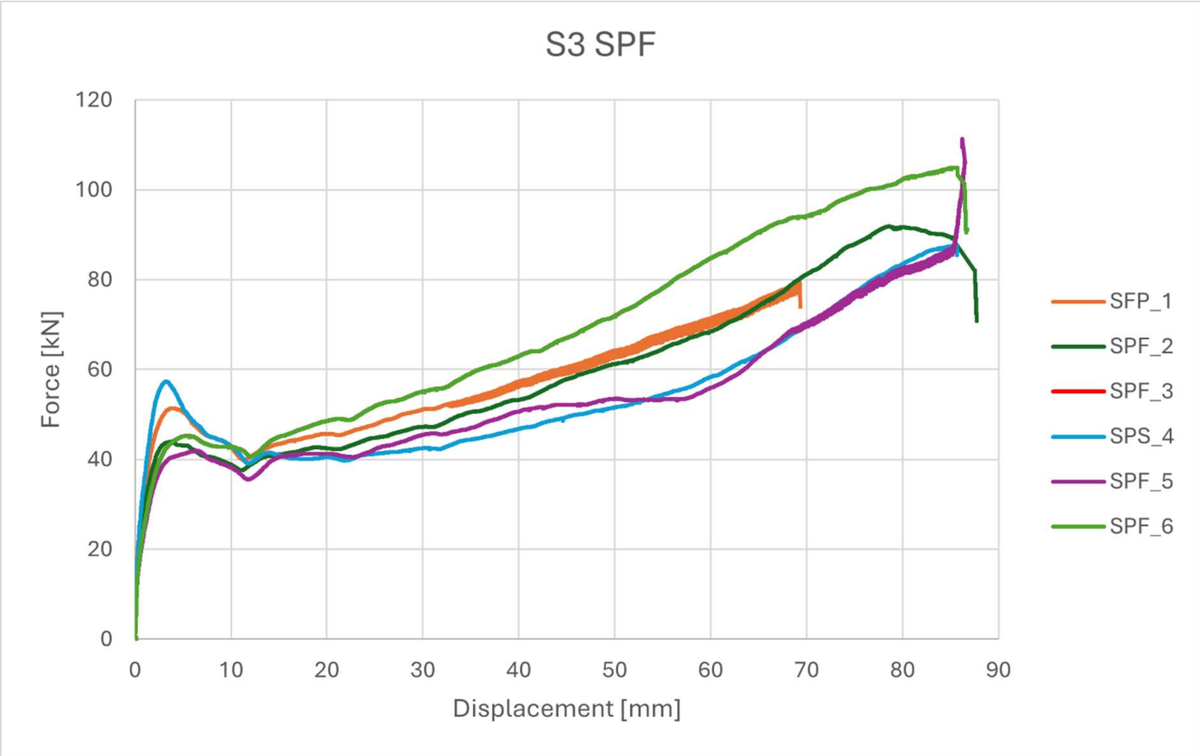
Picture 11:Test results S2 (screws + SHARP METAL) SPF.



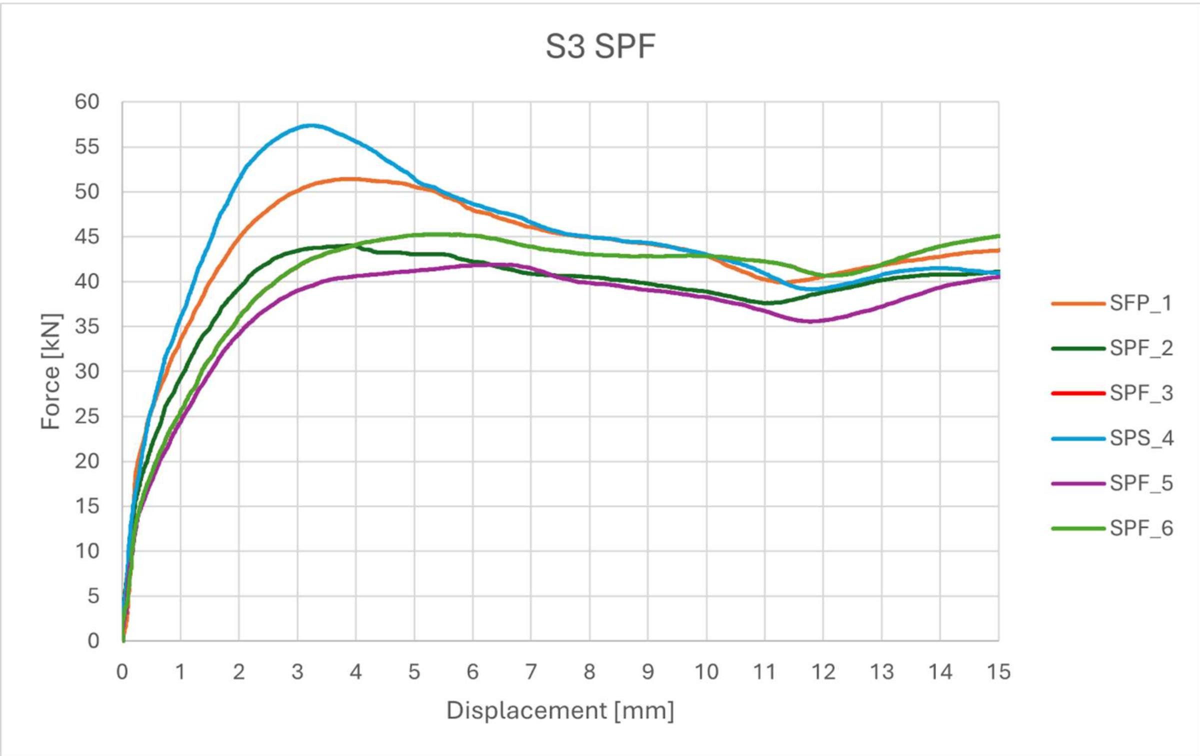
Picture 12:Comparison - test results S2(screws + SHARP METAL). Eu and SPF



Picture 13:Comparison - test results S2(screws + SHARP METAL) Eu and SPF zoom to 15mm.



Picture 14:Test results S3 (screws + SHARP METAL) SPF on lamination Joint.



Picture 15:Test results S3 (screws + SHARP METAL) SPF on lamination Joint zoom to 15mm.

The addition of the SHARP METAL toothed strips provides both the European timber specimens and the SPF specimens with greater resistance at small displacements as well as significantly increased stiffness. In the 0–10 mm range, a much stiffer behaviour is observed, with higher force values and a resistance peak occurring at approximately 4–5 mm, which reasonably corresponds to the spacing between the teeth of the toothed strips.

In European timber, the peak is less pronounced, although the overall behaviour remains similar and the relative increase in resistance is comparable. The point corresponding to a displacement of 4–5 mm marks a degradation of the initial stiffness branch of the curve, highlighting the same phenomenon observed in the SPF timber specimens.

The presence of the joint between the boards does not appear to significantly affect the mechanical behavior of the connection. The variations between the test results are consistent with the statistical variability of the tests.

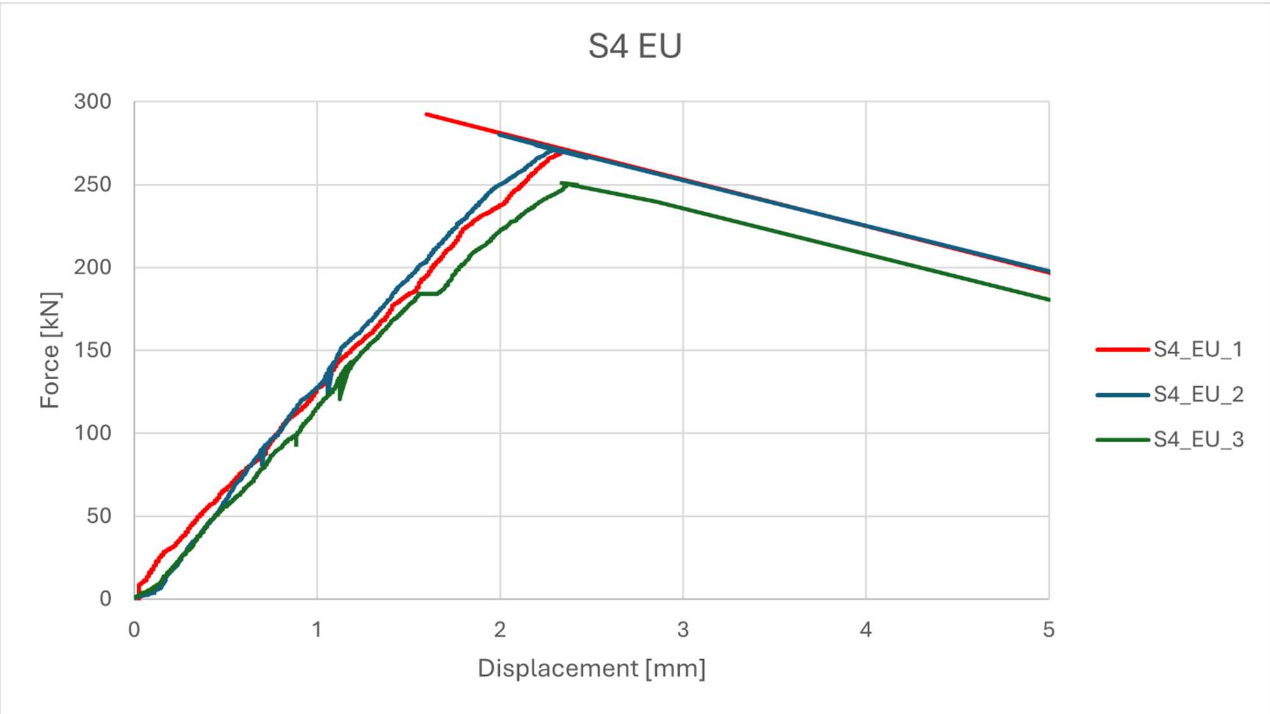
The tests of Series 4 exhibit a very high peak load, on the order of 270 kN, with a maximum displacement below 2.5 mm. A slight negative displacement is observed at the moment of failure, likely caused by the elastic release of the testing equipment during the brittle failure of the specimen.

The comparison between the results obtained with SHARP METAL and those from specimens bonded with epoxy resin confirms the expected behaviour. The bonded connection shows a strength governed by the shear capacity of the wood fibres (2.5-3.5MPa), achieving excellent performance in terms of both strength and stiffness.

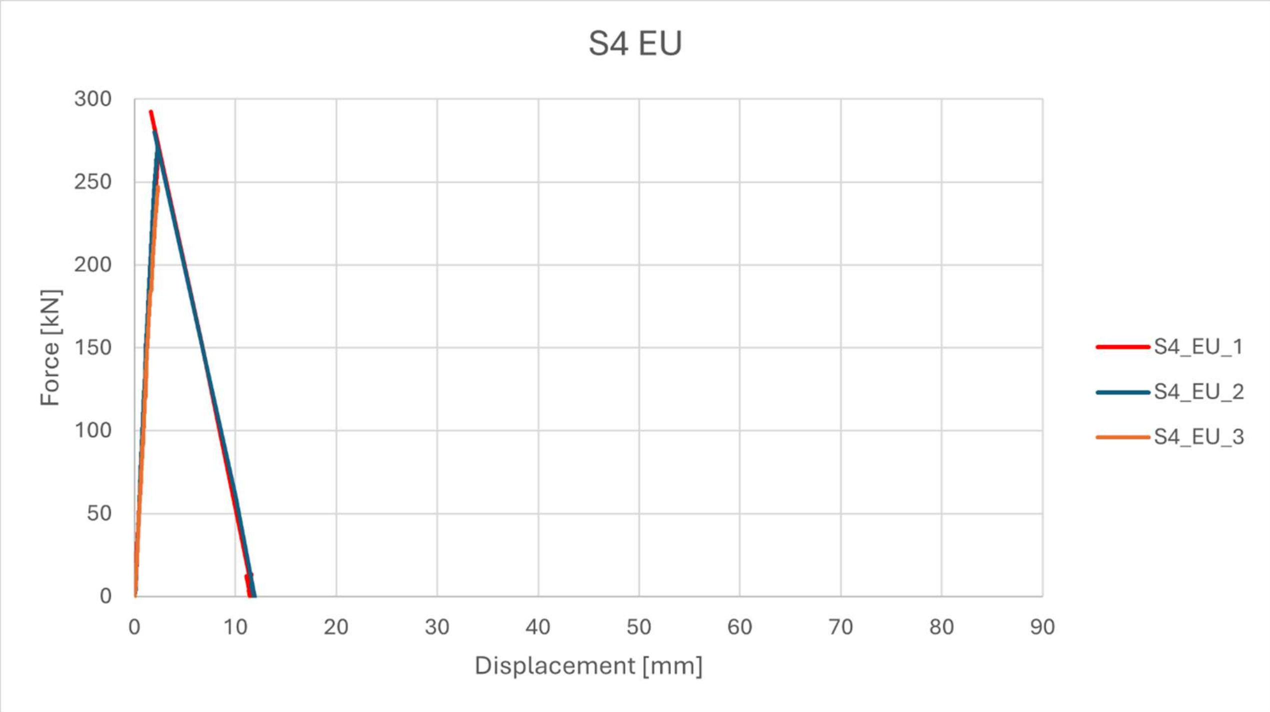
It is assumed that the bonded connection develops an effective anchorage length related to the thickness of the first lamella of the CLT panel. In accordance with the recommendations of the German national standards (DIN1052), a conservative effective length equal to 15 times the thickness of the first board is adopted.

With this assumption, and adopting an average shear strength of 4.0 MPa, a reasonable estimate of the failure load is obtained.

The dispersion of the results across all series—aside from some initial gaps due to specimen settling—is limited, with no evident outliers. Overall, the data appear well distributed, consistent, and repeatable.

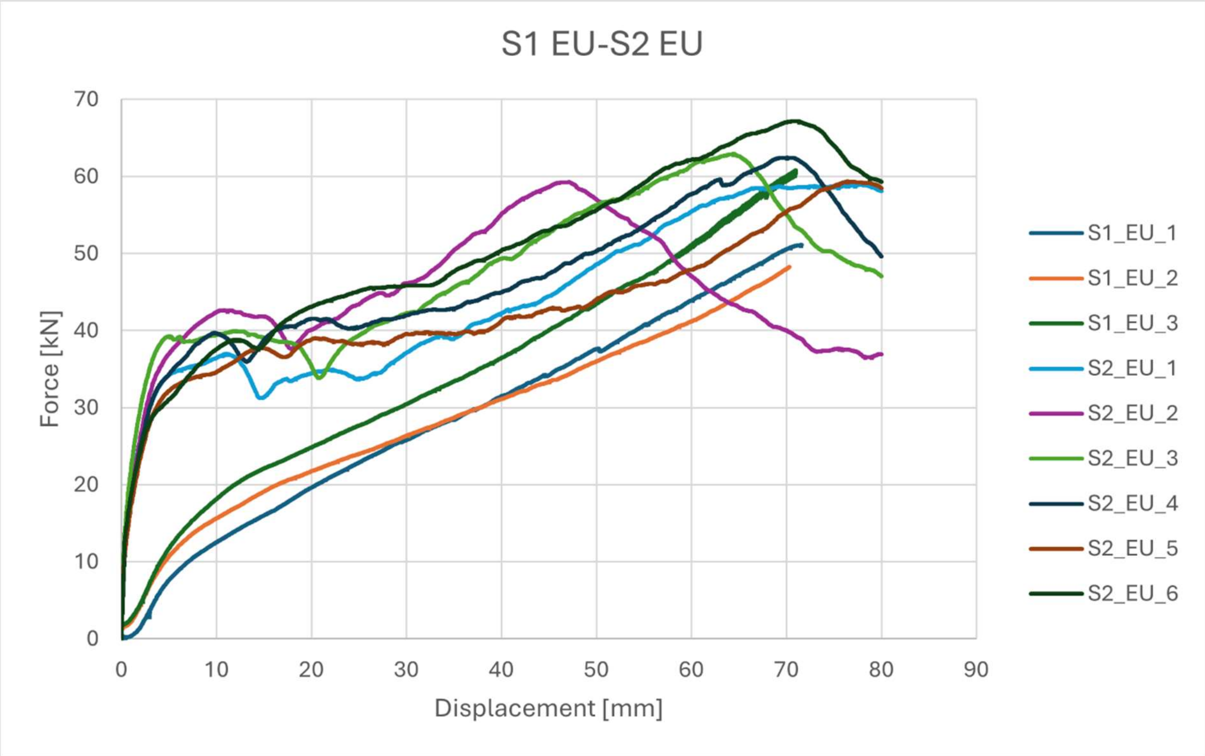


Picture 16:Test results S4 (screws + glue) European Spruce

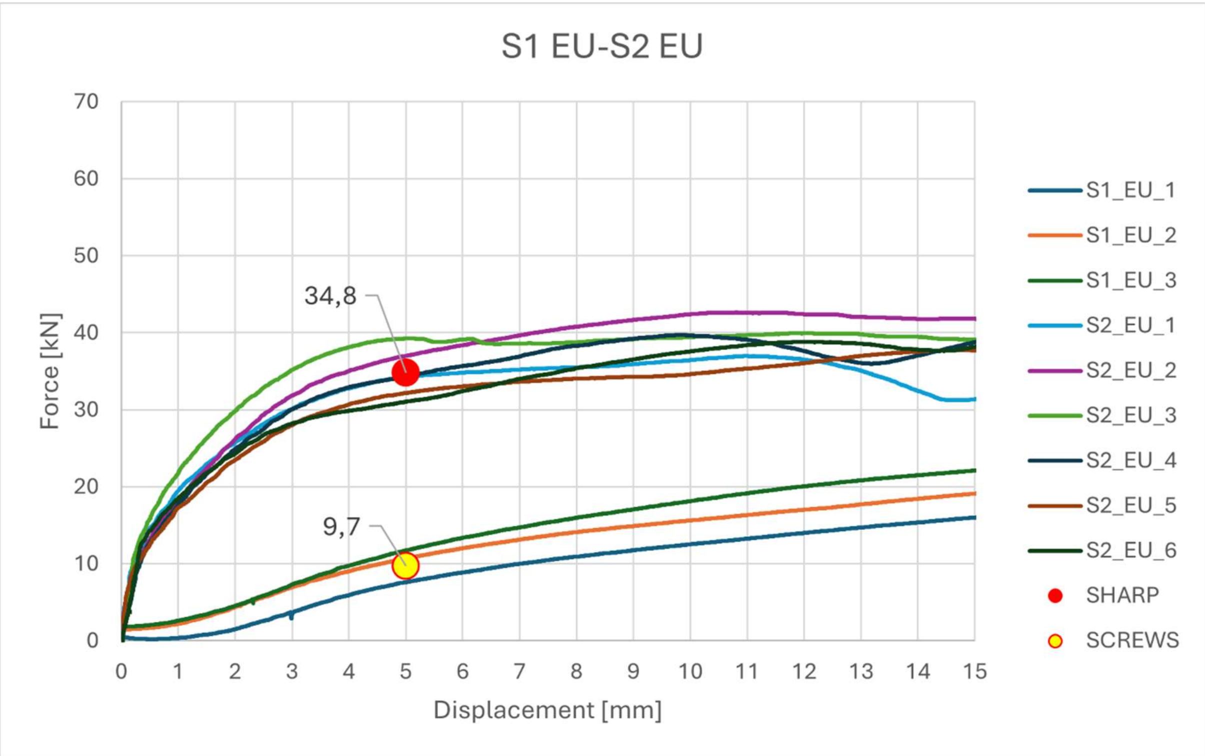


Picture 17:Test results S4 (screws + glue) European Spruce zoom to 15mm.

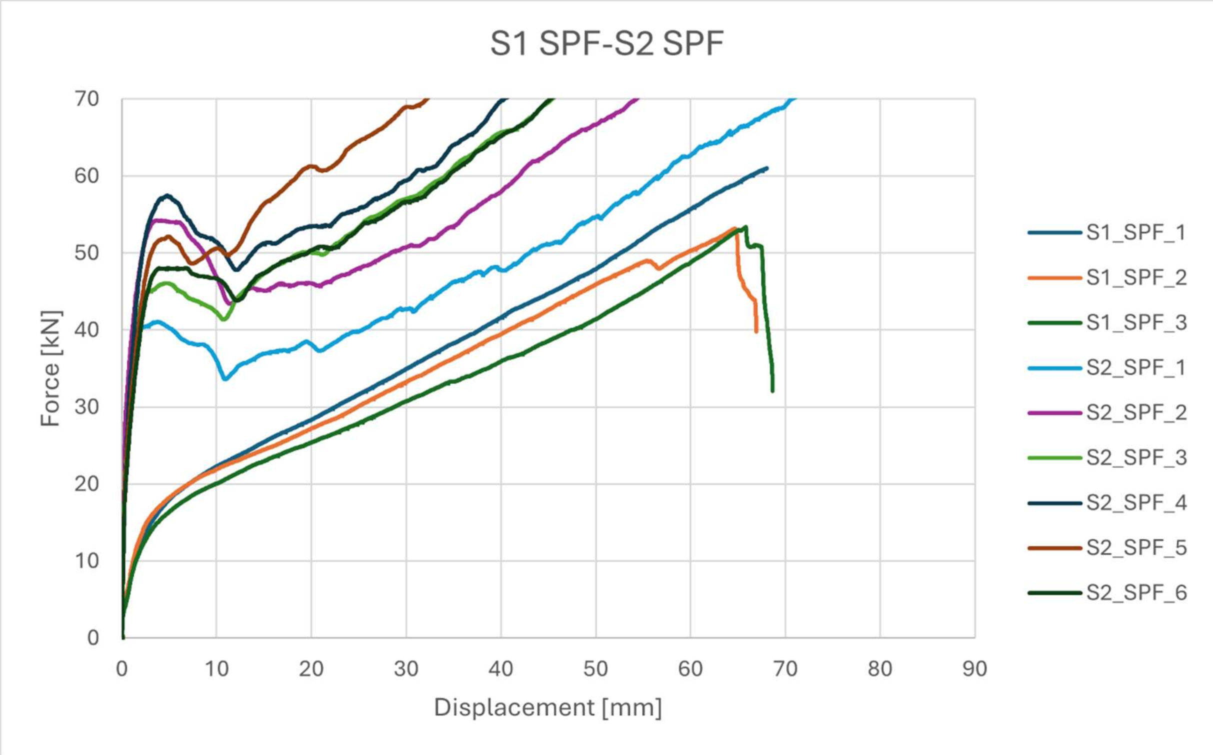
2.1. Comparisons S1 – S2 (Lower bound limit)



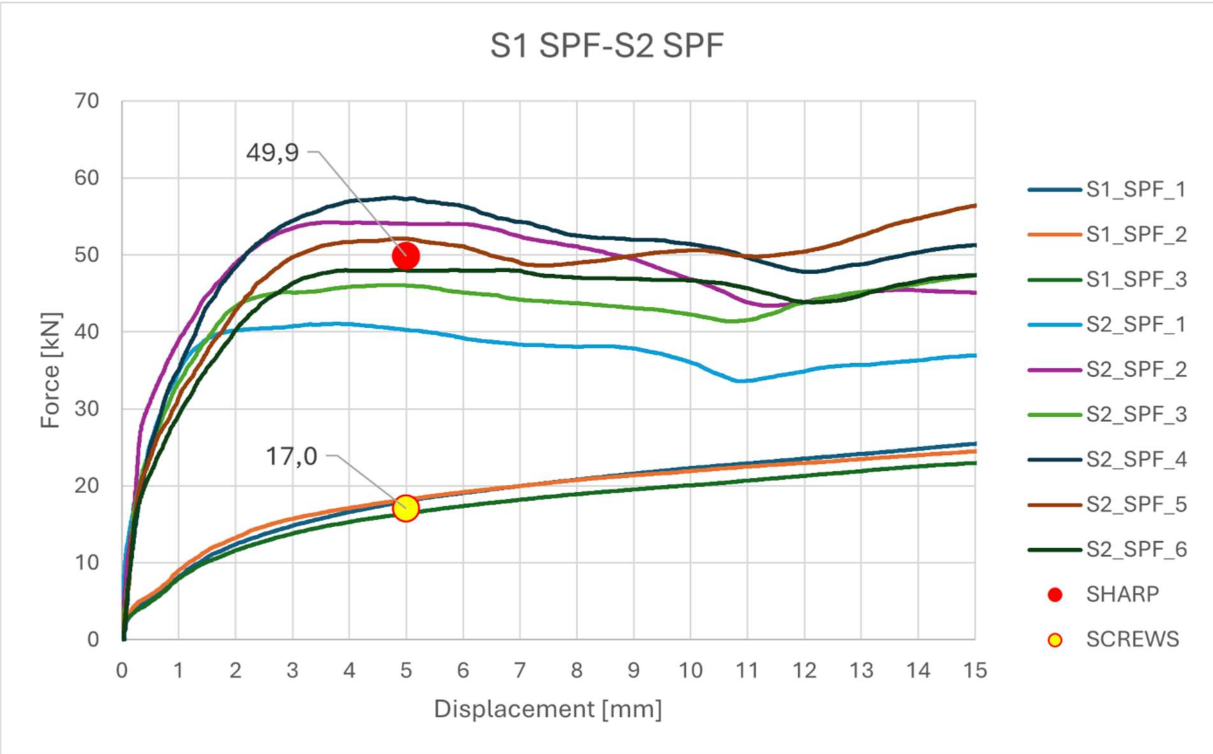
Picture 18:Comparison - test results S1 (screws) - S2 (screws + SHARP METAL) Eu.



Picture 19:Comparison - test results S1 (screws) - S2 (screws + SHARP METAL) Eu zoom to 15mm

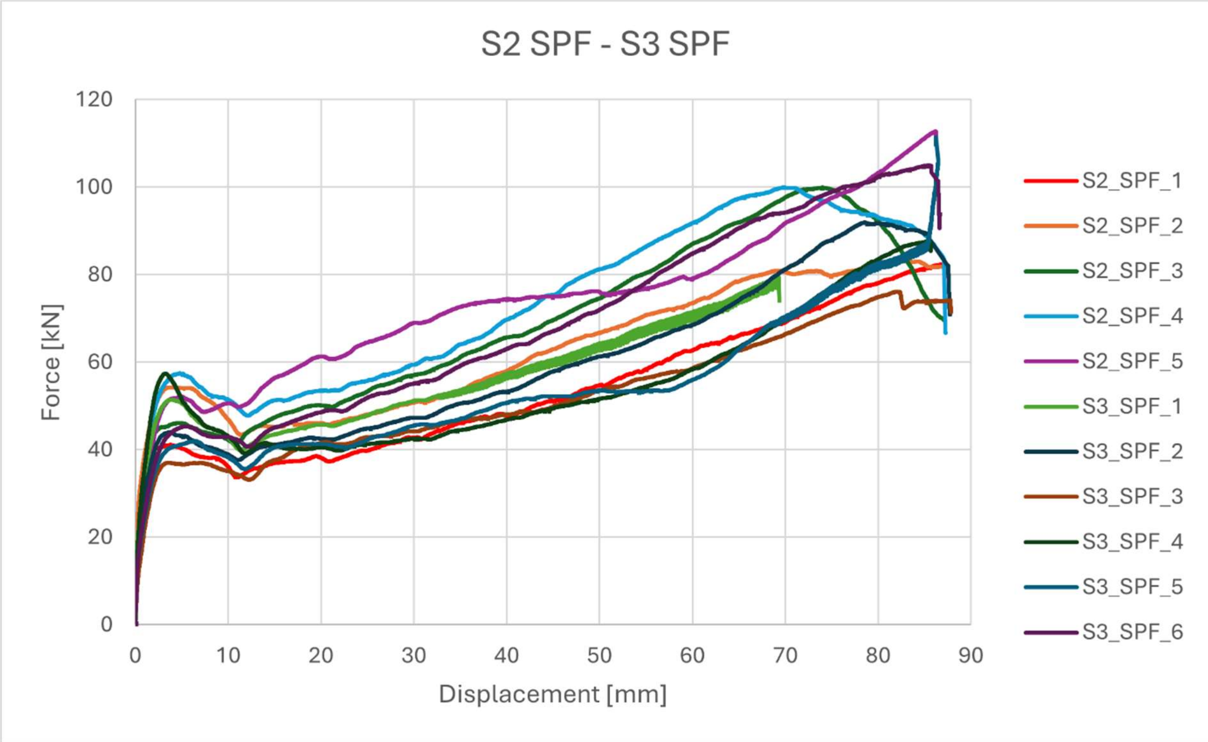


Picture 20:Comparison - test results S1 (screws) - S2 (screws + SHARP METAL) SPF.

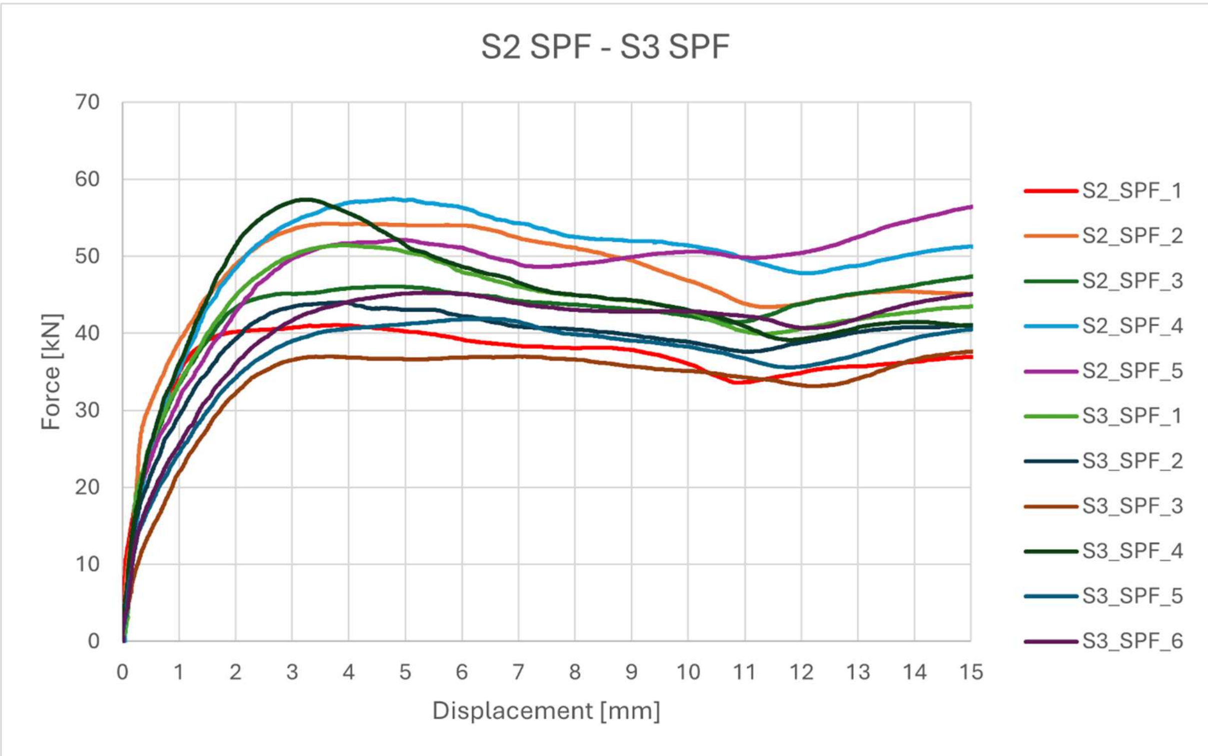


Picture 21:Comparison - test results S1 (screws) - S2 (screws + SHARP METAL) SPF zoom to 15mm.

2.2. Comparisons S2 – S3 (Lamination joint influence)

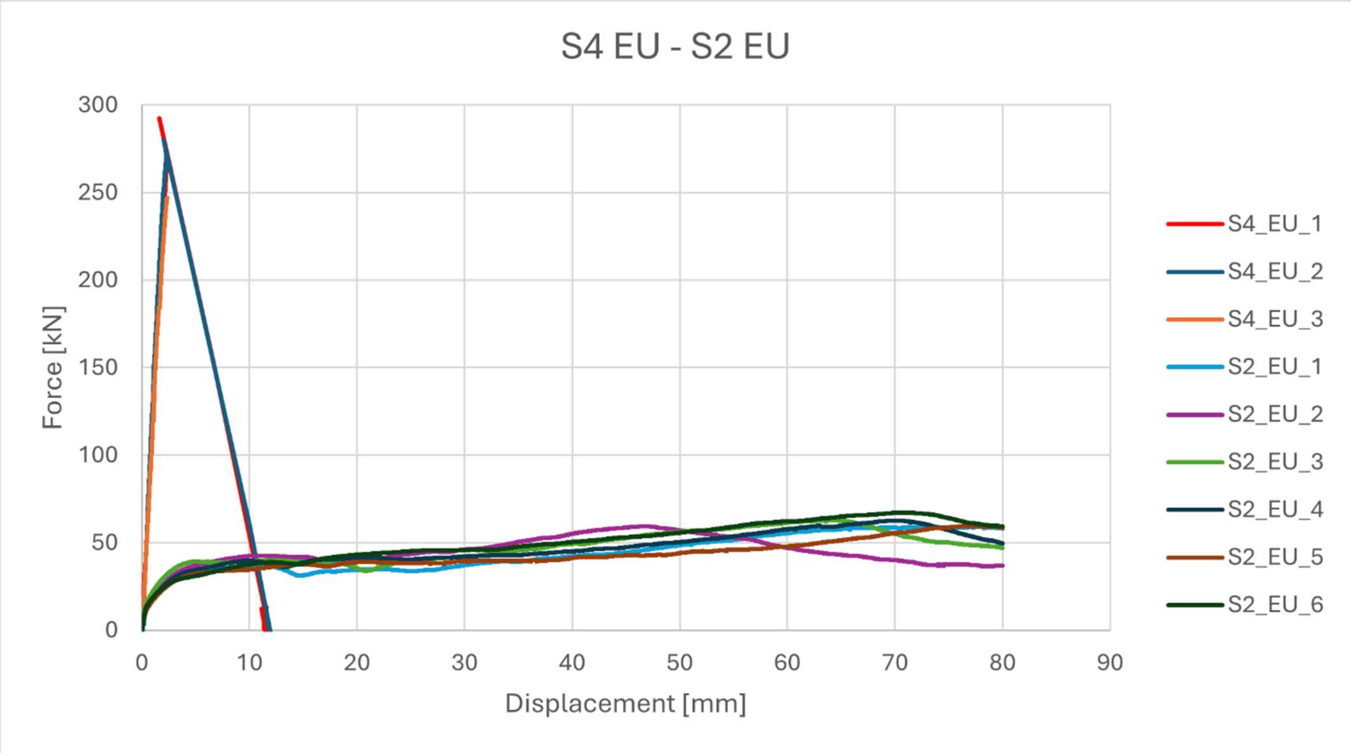


Picture 22:Comparison - test results S2 (screws+ SHARP METAL) – S3 (screws + SHARP METAL on the lamination joint) SPF.

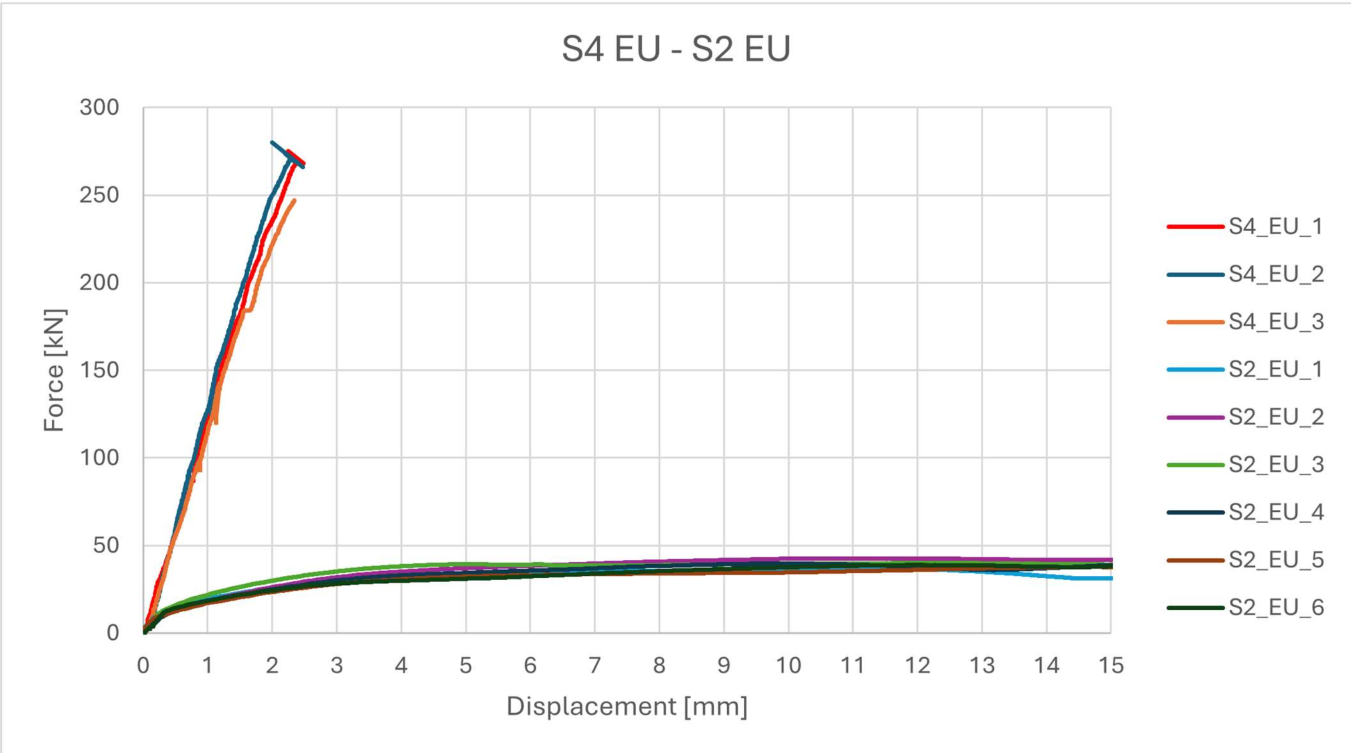


Picture 23:Comparison - test results S2 (screws + SHARP METAL) – S3 (screws + SHARP METAL on the lamination joint) SPF zoom to 15mm.

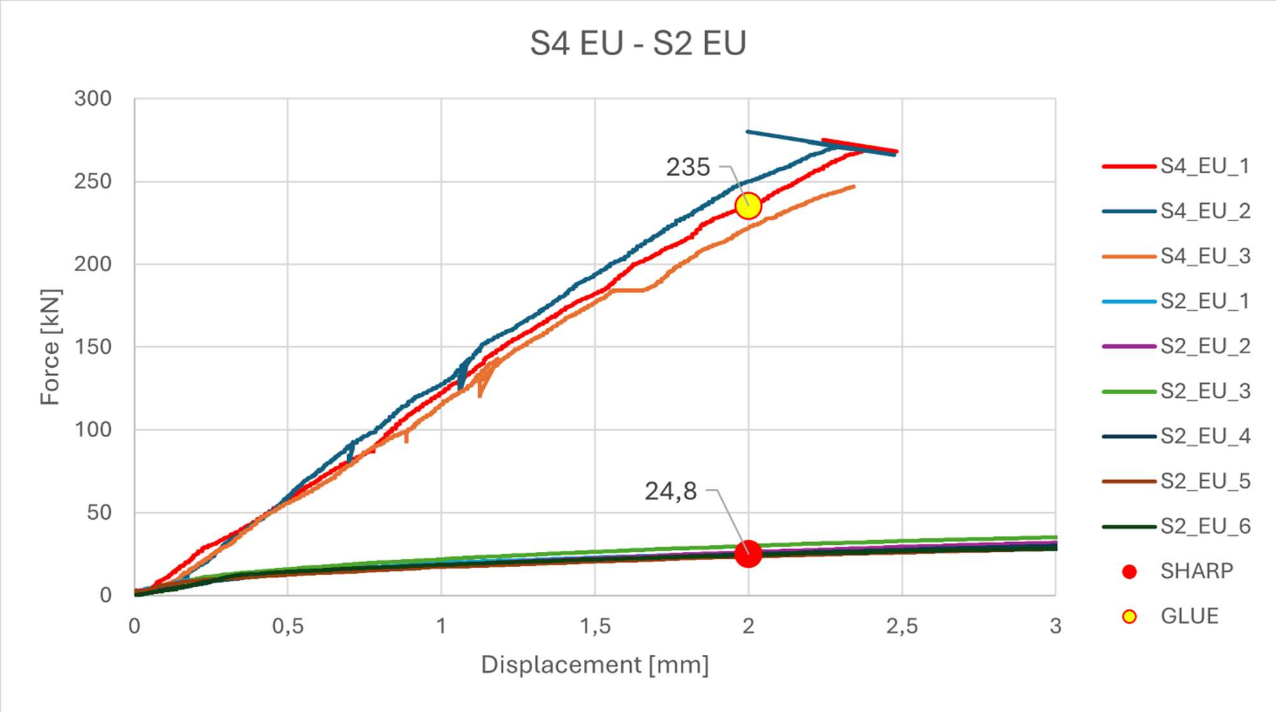
2.3. Comparisons S2 – S4 (Upper bound limit)



Picture 24:Comparison - test results S4 (glue) - S2 (screws + SHARP METAL) EU.



Picture 25:Comparison - test results S4 (glue) - S2 (screws + SHARP METAL) EU zoom to 10mm.

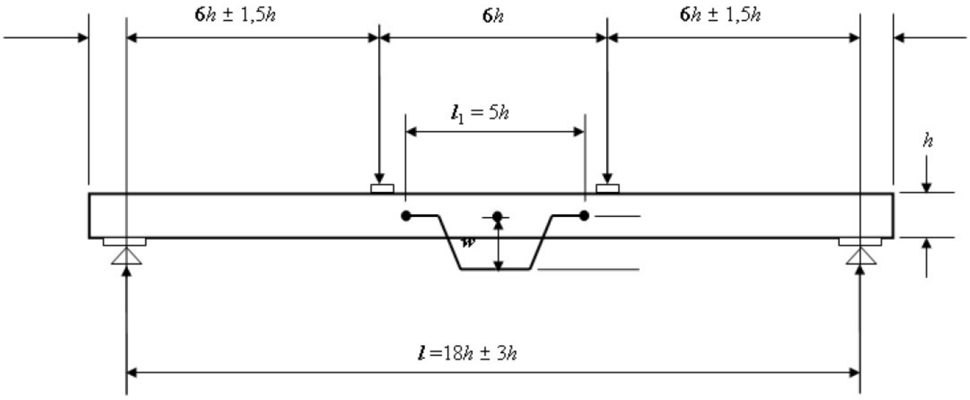


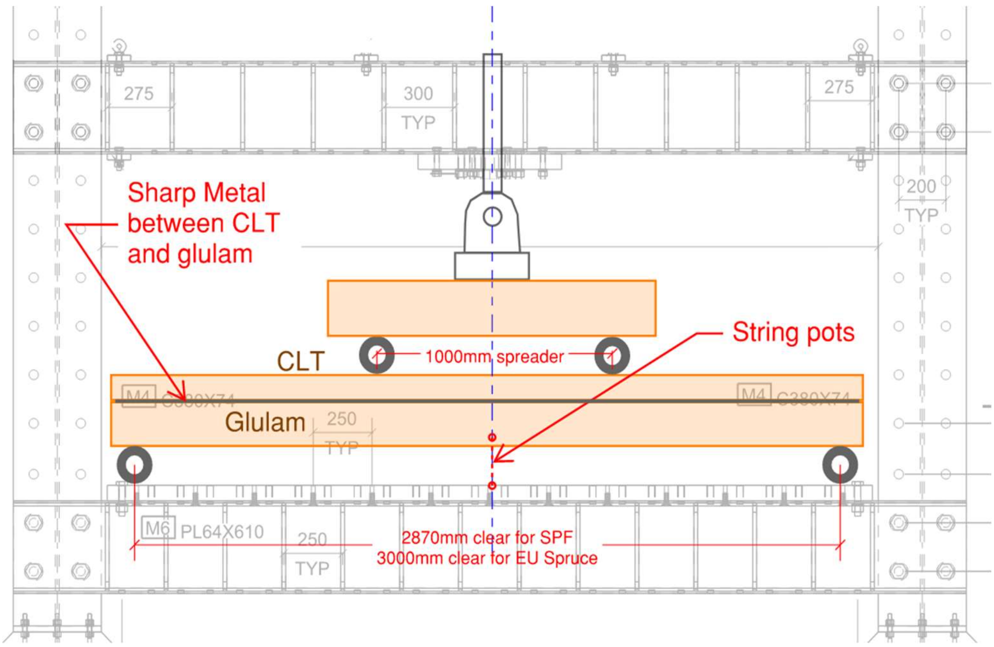
Picture 26: Comparison - test results S4 (glue) - S2 (screws + SHARP METAL) EU zoom to 3mm.

3. MID SCALE TESTS

The mid-scale tests were carried out using a geometry designed to maximise the potential of the testing setup. The tested elements had a clear span of 3.0 m for the European timber (EU) specimens and 2.87 m for the SPF specimens. This difference does not alter the overall structural behaviour, but it must be taken into account when performing the analyses. The evaluation of the results was conducted in accordance with the procedures specified in EN 408:2010.

The load was applied by a hydraulic actuator, which transferred the force through a distribution beam positioned approximately at one-third of the span. The deformation of this distribution beam does not influence the overall interpretation of the tests, since the displacement readings were taken using two transducers placed between the beam and the lower crosshead of the testing frame.





Picture 27: Mid-scale testing, four point bending test setup.

M1 = CLT and GL joined only with 90° screws

Name	TIMBER	TYPE/GRADE CLT	GL	CLT DENSITY [kg/m³]	GL DENSITY [kg/m³]	CONNECTION
M1_EU_1 M1_EU_2 M1_EU_3	EU	C24 3 PLY 30/30/30	GL24h			20 TBS MAX 8x240

M2 = CLT and GL joined only with 90° screws and SHARP METAL

Name	TIMBER	TYPE/GRADE CLT	GL	CLT DENSITY [kg/m³]	GL DENSITY [kg/m³]	CONNECTION
M2_EU_1 M2_EU_2 M2_EU_3	EU	C24 3 PLY 30/30/30	GL24h			20 TBS MAX 8x240+SHARP METAL (optimized 1/3 at the support with 2 stripes and 1 in the central third)
M2_SPF_1 M2_SPF_2 M2_SPF_3	NA	No2 & btr				20 TBS MAX 8x240+SHARP METAL (optimized 1/3 at the support with 2 stripes and 1 in the central third)

M3 = CLT with lamination joint and GL joined with 90° screws and SHARP METAL

Name	TIMBER	TYPE/GRADE CLT	GL	CLT DENSITY [kg/m³]	GL DENSITY [kg/m³]	CONNECTION
M3_SPF_1 M3_SPF_2 M3_SPF_3	NA	No2 & btr				20 TBS MAX 8x240+SHARP METAL (optimized 1/3 at the support with 2 stripes and 1 in the central third)

M4 = CLT joined to GL with the same 90° screws as S1, plus glue

Name	TIMBER	TYPE/GRADE CLT	GL	CLT DENSITY [kg/m³]	GL DENSITY [kg/m³]	CONNECTION
M3_SPF_1 M3_SPF_2 M3_SPF_3	NA	No2 & btr				20 TBS MAX 8x240+GLUE

Table 5:Mid- scale test geometry and samples composition.

The mid-span bending tests show, in some cases, a rather high variability in ultimate strength. However, the elastic-phase behaviour is generally repeatable, with values falling within a relatively narrow variability range.

M1 = CLT and GL joined only with 90° screws

Name	F_{max} [kN]	V_{max} [mm]	F_{01} [kN]	v_{01} [mm]	F_{04} [kN]	v_{04} [mm]	EI [Nmm²]	$v_{l/300}$ [mm]	$F_{l/300}$ [kN]	$v_{l/500}$ [mm]	$F_{l/500}$ [kN]
M1_EU_1	79,9	26,6	8,0	1,2	32	9,5	1,80E+11	10,0	33,4	6,0	21,7
M1_EU_2	90,8	26,1	9,1	1,2	36,3	9,6	2,03E+11	10,0	37,7	6,0	25,0
M1_EU_3	142,4	47,1	14,2	2,9	57	16,8	1,92E+11	10,0	36,0	6,0	23,7

M2 = CLT and GL joined only with 90° screws and SHARP METAL

Name	F_{max} [kN]	V_{max} [mm]	F_{01} [kN]	v_{01} [mm]	F_{04} [kN]	v_{04} [mm]	EI [Nmm²]	$v_{l/300}$ [mm]	$F_{l/300}$ [kN]	$v_{l/500}$ [mm]	$F_{l/500}$ [kN]
M2_EU_1	142	30,4	14,2	1,8	56,8	8,6	3,92E+11	10,0	64,0	6,0	42,5
M2_EU_2	146	29,4	14,6	1,9	58,4	8,9	3,91E+11	10,0	64,0	6,0	42,6
M2_EU_3	136,5	30,9	13,7	4,2	54,6	11,8	3,37E+11	10,0	63,6	6,0	42,7
M2_SPF_1	145,2	36,0	14,5	2,8	58,1	17,5	1,73E+11	9,6	34,8	5,7	23,7
M2_SPF_2	144,7	30,9	14,5	2,0	57,9	13,5	2,21E+11	9,6	45,0	5,7	33,1
M2_SPF_3	115,6	28,9	14,5	1,7	57,9	8,2	3,90E+11	9,6	52,7	5,7	34,9

M3 = CLT with lamination joint and GL joined with 90° screws and SHARP METAL

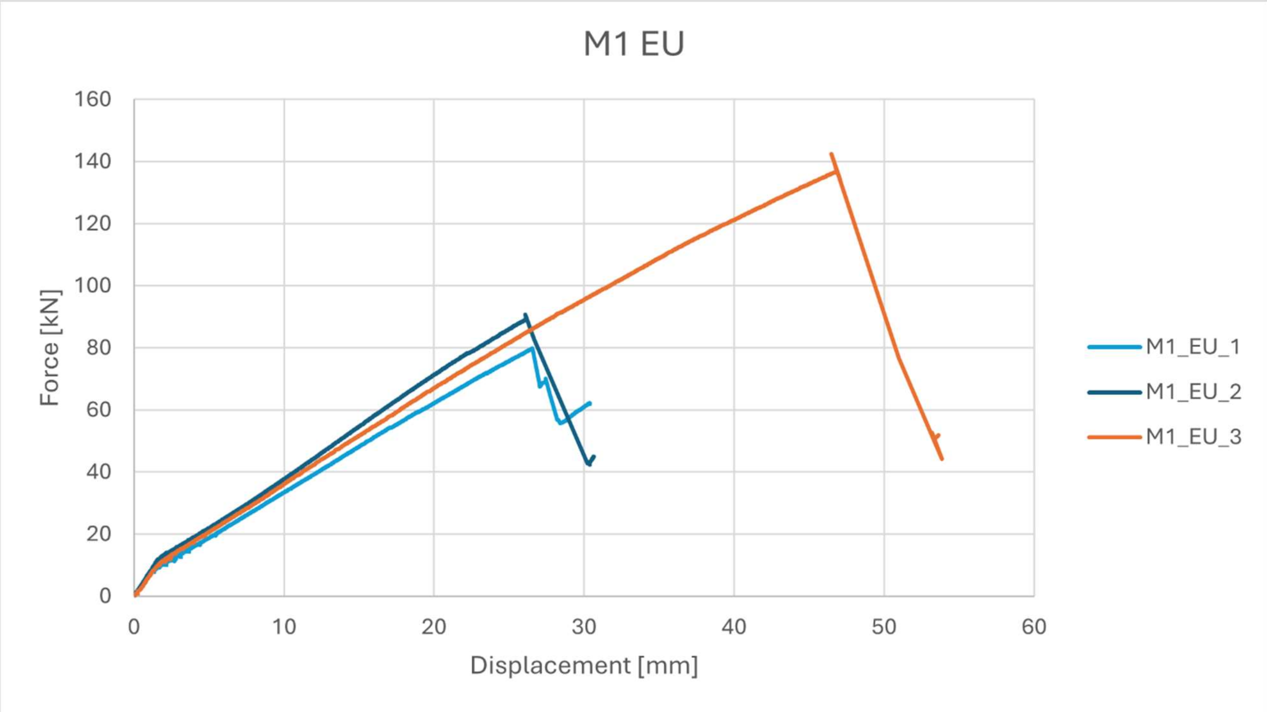
Name	F_{max} [kN]	V_{max} [mm]	F_{01} [kN]	v_{01} [mm]	F_{04} [kN]	v_{04} [mm]	EI [Nmm²]	$v_{l/300}$ [mm]	$F_{l/300}$ [kN]	$v_{l/500}$ [mm]	$F_{l/500}$ [kN]
M3_SPF_1	130,9	27,1	13,1	1,8	52,4	8,3	3,78E+11	9,6	58,9	5,7	38,2
M3_SPF_2	150,5	34,5	15,1	2,4	60,2	10,6	3,43E+11	9,6	55,7	5,7	35,5
M3_SPF_3	106,4	20,0	10,6	1,4	42,6	6,4	3,99E+11	9,6	59,3	5,7	38,7

M4 = CLT joined to GL with the same 90° screws as S1, plus glue

Name	F_{max} [kN]	V_{max} [mm]	F_{01} [kN]	v_{01} [mm]	F_{04} [kN]	v_{04} [mm]	EI [Nmm²]	$v_{l/300}$ [mm]	$F_{l/300}$ [kN]	$v_{l/500}$ [mm]	$F_{l/500}$ [kN]
M3_SPF_1	164	27,1	16,4	1,8	65,6	7,7	5,25E+11	10,0	84,2	6,0	51,7
M3_SPF_2	196	34,5	19,6	2,3	78,4	9,4	5,21E+11	10,0	83,3	6,0	50,7
M3_SPF_3	176,5	20,0	17,7	2,2	70,6	8,4	5,30E+11	10,0	83,3	6,0	50,0

Table 6:Mid- scale test results.

For the tests using only screws inserted perpendicular to the panel (M1), two specimens reached comparable ultimate loads (80–90 kN), whereas the third showed a significantly higher value (140 kN). This discrepancy is justified by the intrinsic variability of the bending strength of timber. It is likely that specimen M1_EU_3, thanks to a favourable positioning of defects away from the critical tension zone, avoided premature brittle failure in the tension edge. Although specimen M3 shows a much higher strength compared to the others, its overall stiffness is comparable and fully consistent with the other tests.

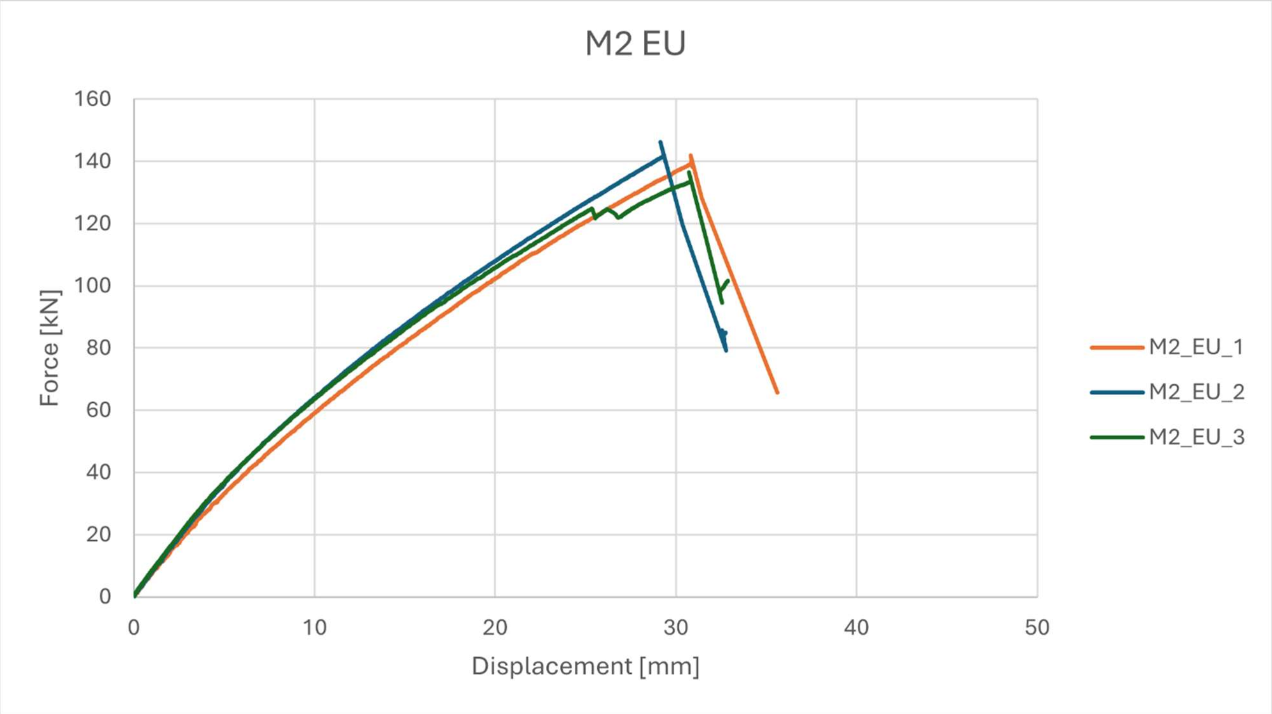


Picture 28:Test results M1 (screws) European Spruce

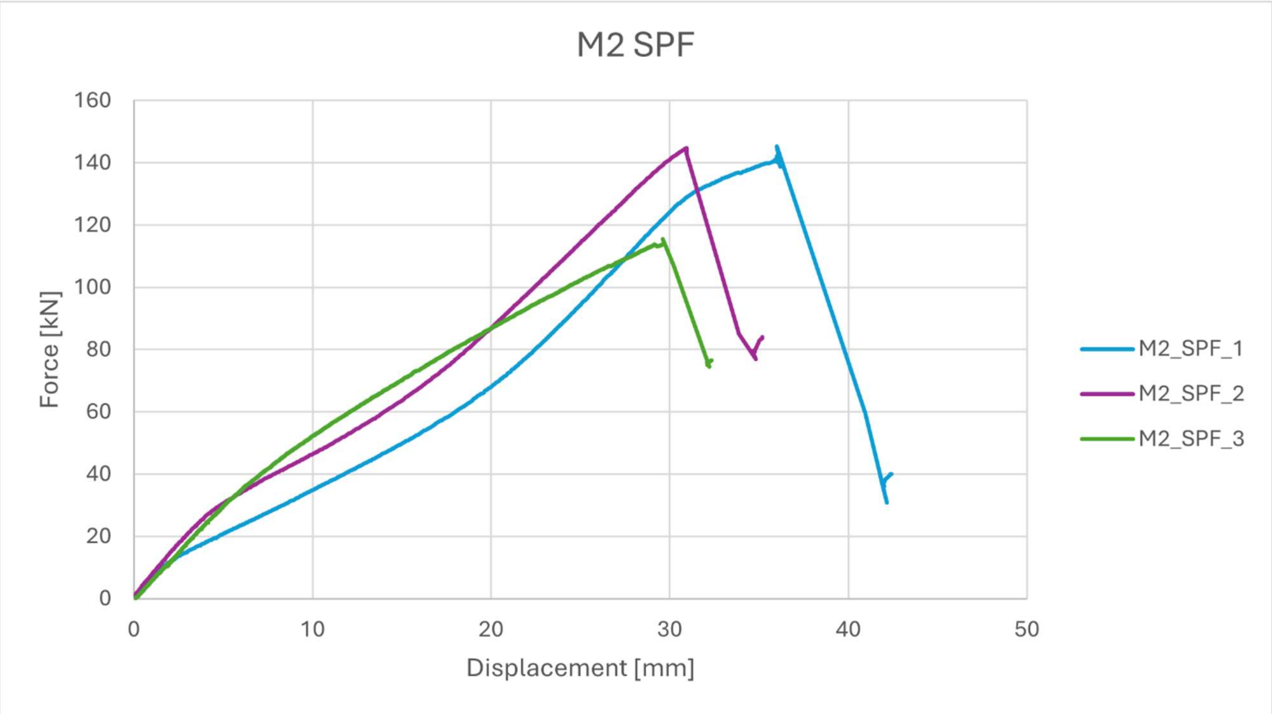
In the tests using the combined contribution of SHARP METAL and screws, both stiffness and bending resistance show a marked increase. Both series exhibit an ultimate capacity that is essentially identical for EU and SPF specimens.
In the case of SPF, the load–displacement curve of two specimens shows a slight inflection in the 15–25 mm displacement range. However, this does not have a relevant influence on the practical interpretation of the structural behaviour.

The presence of the board-to-board joint (M3) does not appear to significantly affect the mechanical response, and the differences with series M2 (without joint) are not statistically significant.

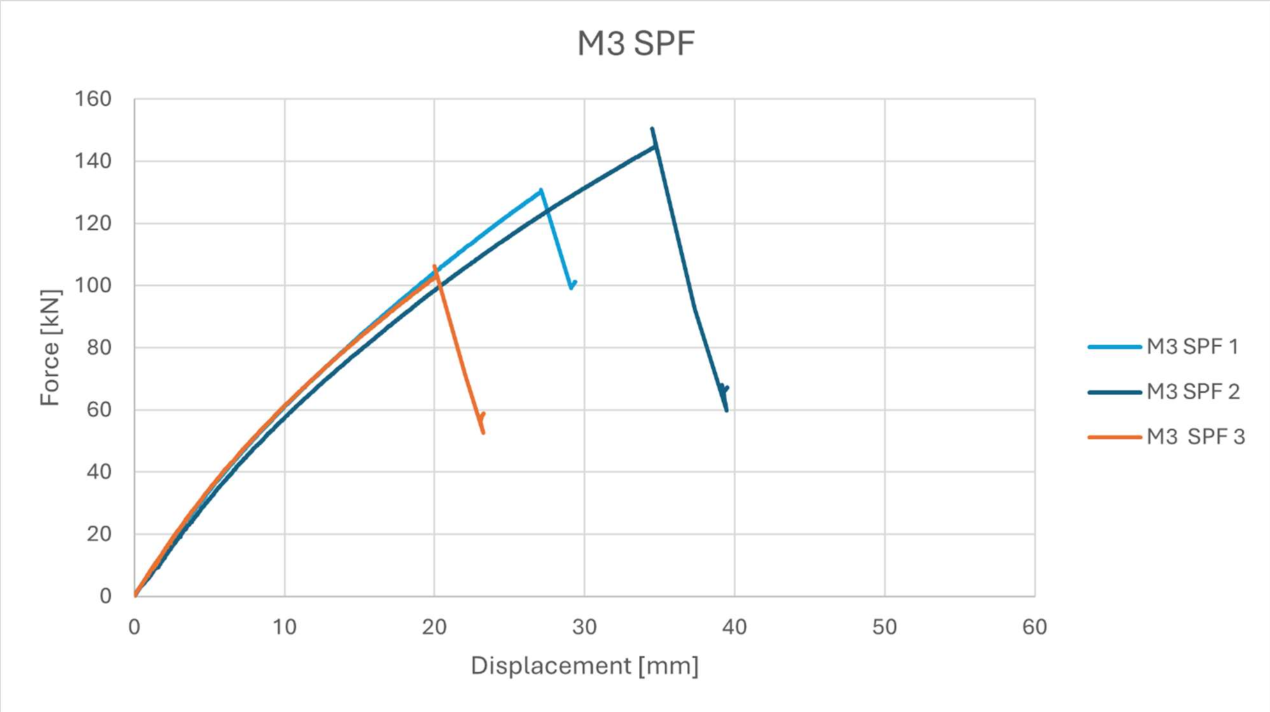
The comparison between SHARP METAL and glued specimens further confirms the extremely stiff and resistant behaviour of the glued system. However, due to the configuration of the system and the bending-driven failure mode, it is not possible to fully exploit the connection’s capacity in terms of strength.



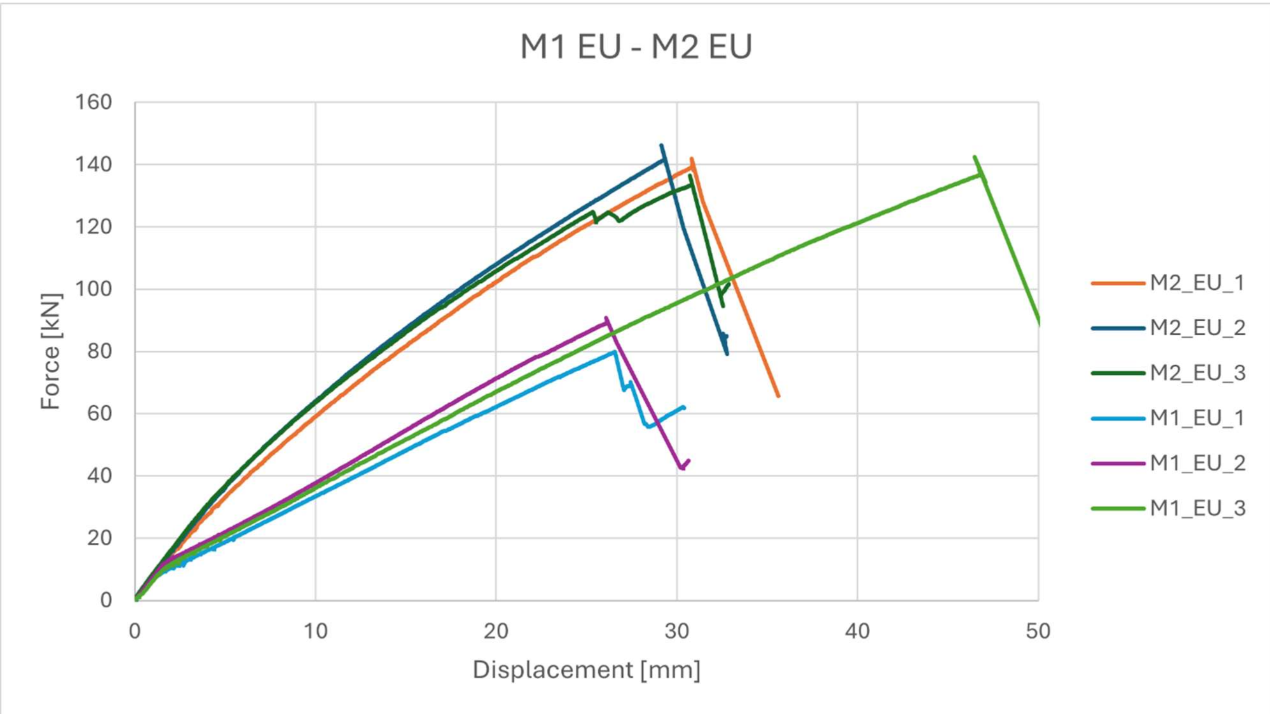
Picture 29:Mid-scale tests M2 (screws) European timber.



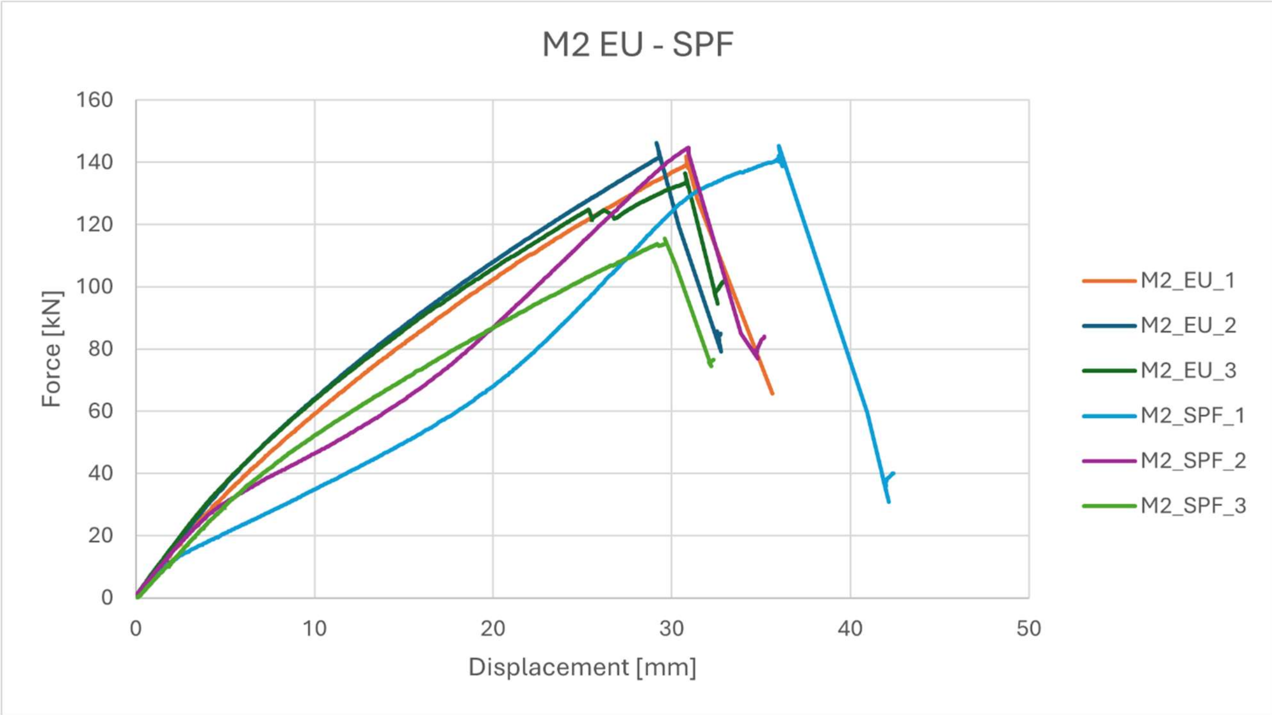
Picture 30: Mid-scale tests M2 (screws) SPF timber.



Picture 31: Mid-scale tests M3 (screws) SPF timber with lamination joint.

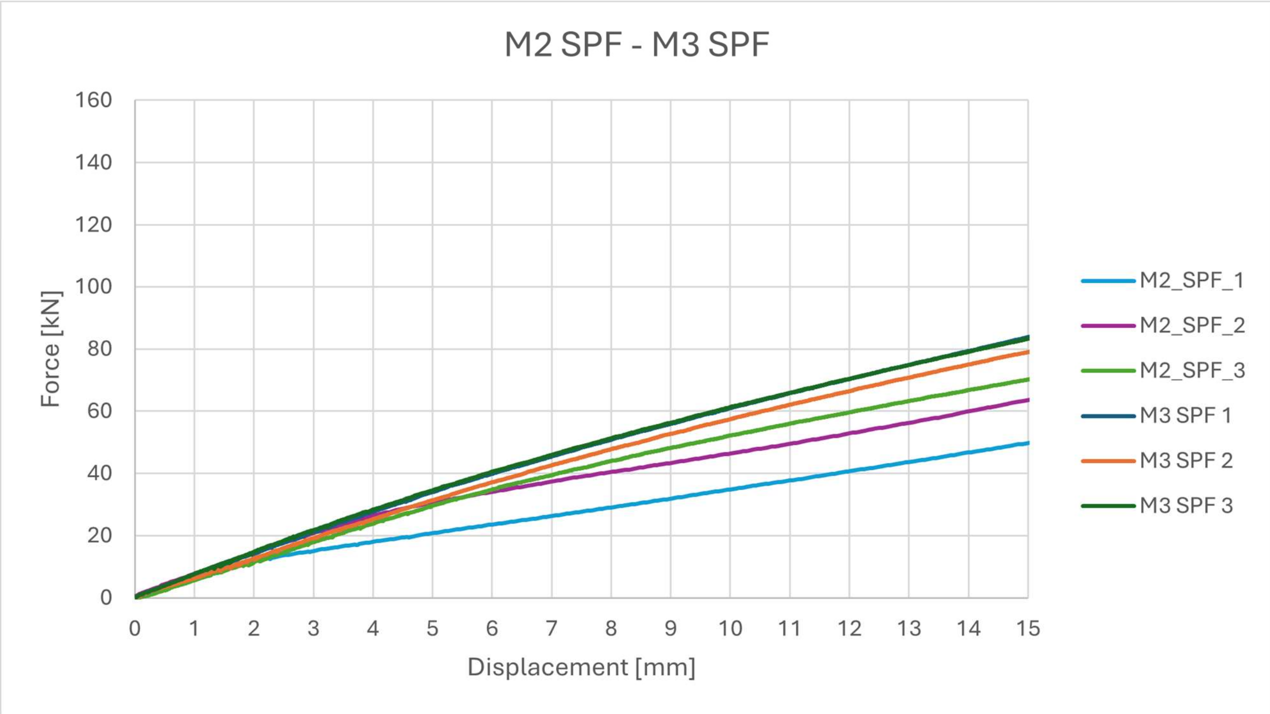


Picture 32: Comparison - test results M1 (screws) - M2 (screws + SHARP METAL) Eu timber.

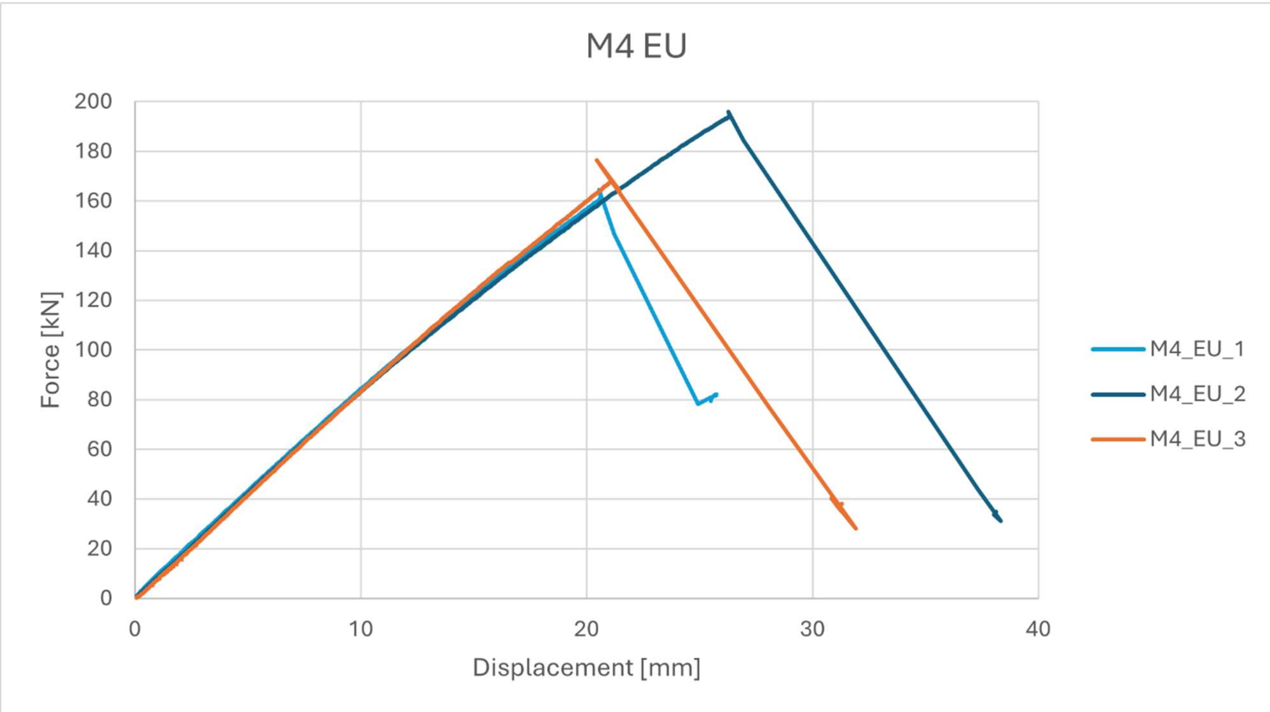


Picture 33:Comparison - test results M2 (screws + SHARP METAL) – EU-SPF timber.

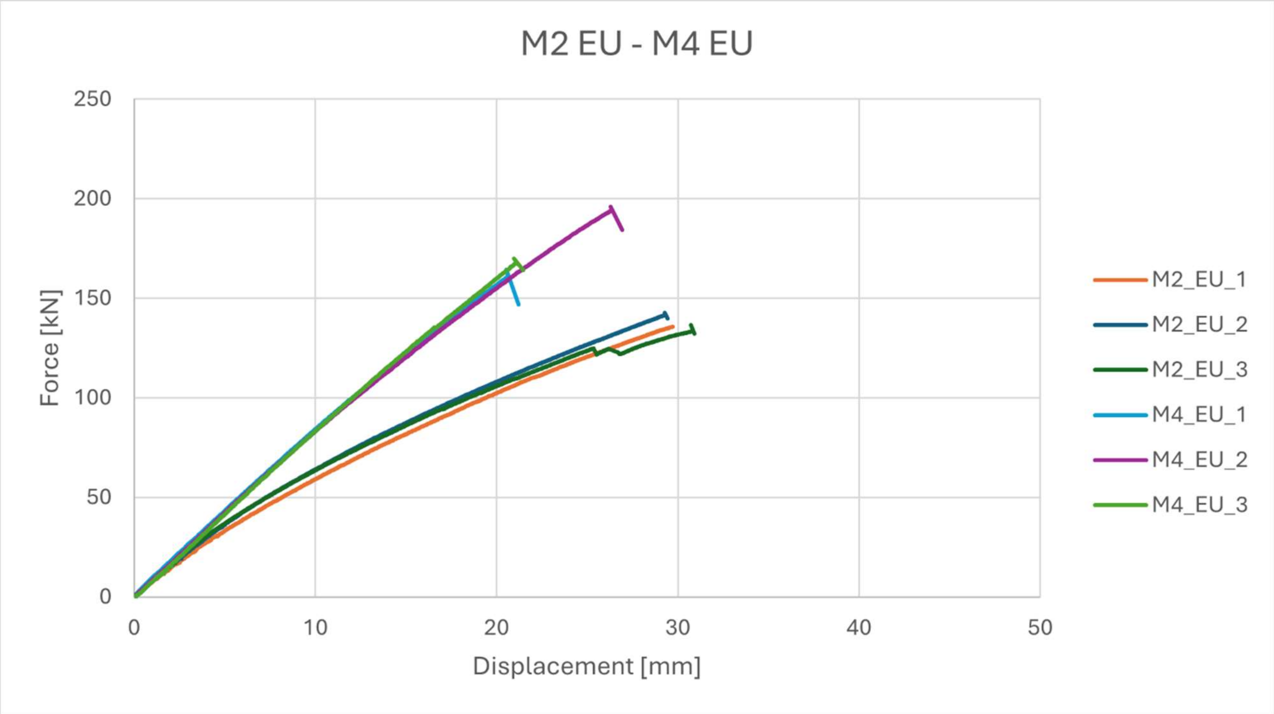
Picture 34: Comparison - results M2 (screws + SHARP METAL)M3 (screws+SHARP METAL on lamination joint) – SPF timber.



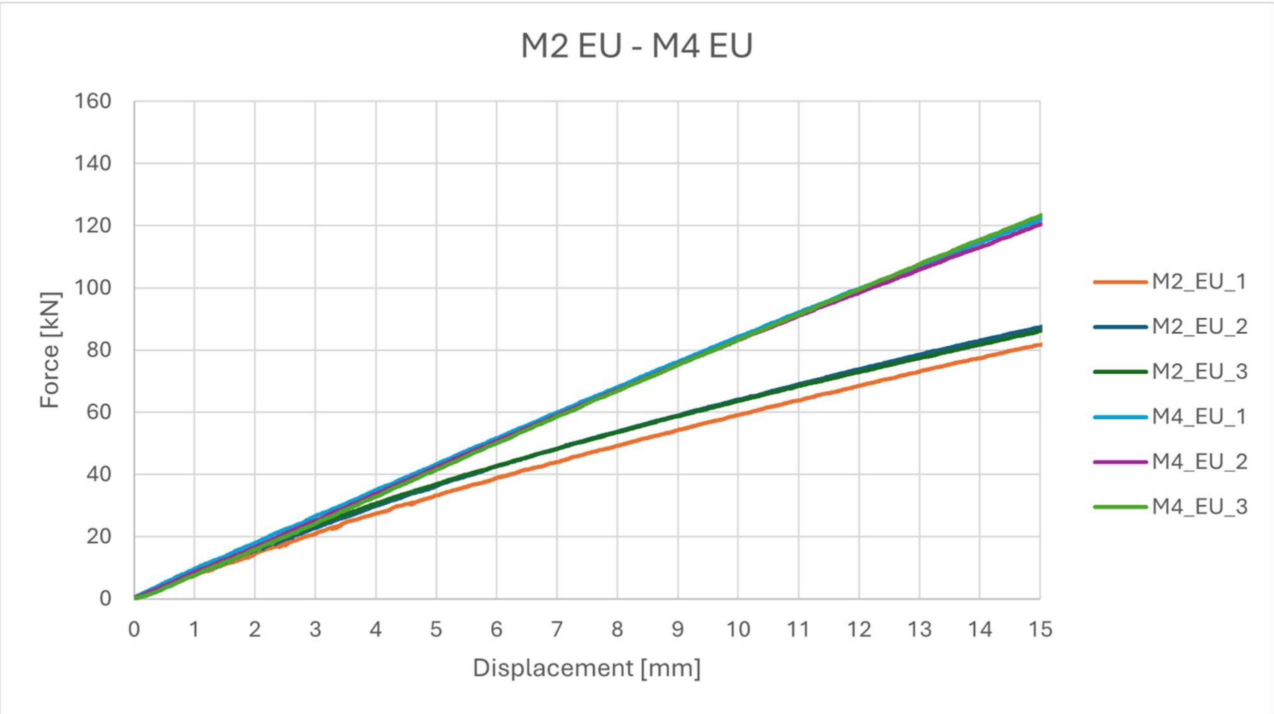
Picture 35: Comparison - test results M2(screws + SHARP METAL) - M3 (screws+SHARP METAL on lamination joint) – SPF timber zoom to 15mm.



Picture 36:Mid-scale tests M4 (screws + glue) EU timber.



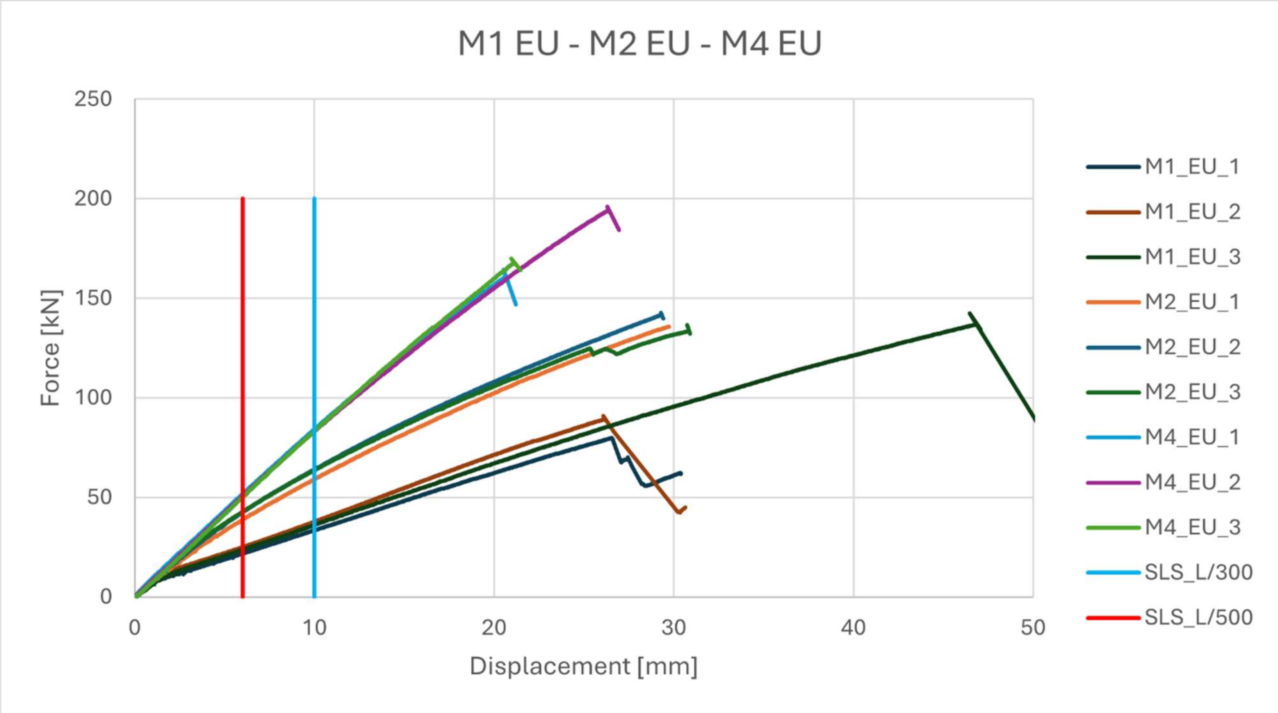
Picture 37: Comparison - results M2 (screws + SHARP METAL)-M4 (screws+glue) – EU timber.



Picture 38: Comparison - results M2 (screws + SHARP METAL)-M4 (screws+glue) – EU timber, zoom to 15mm.

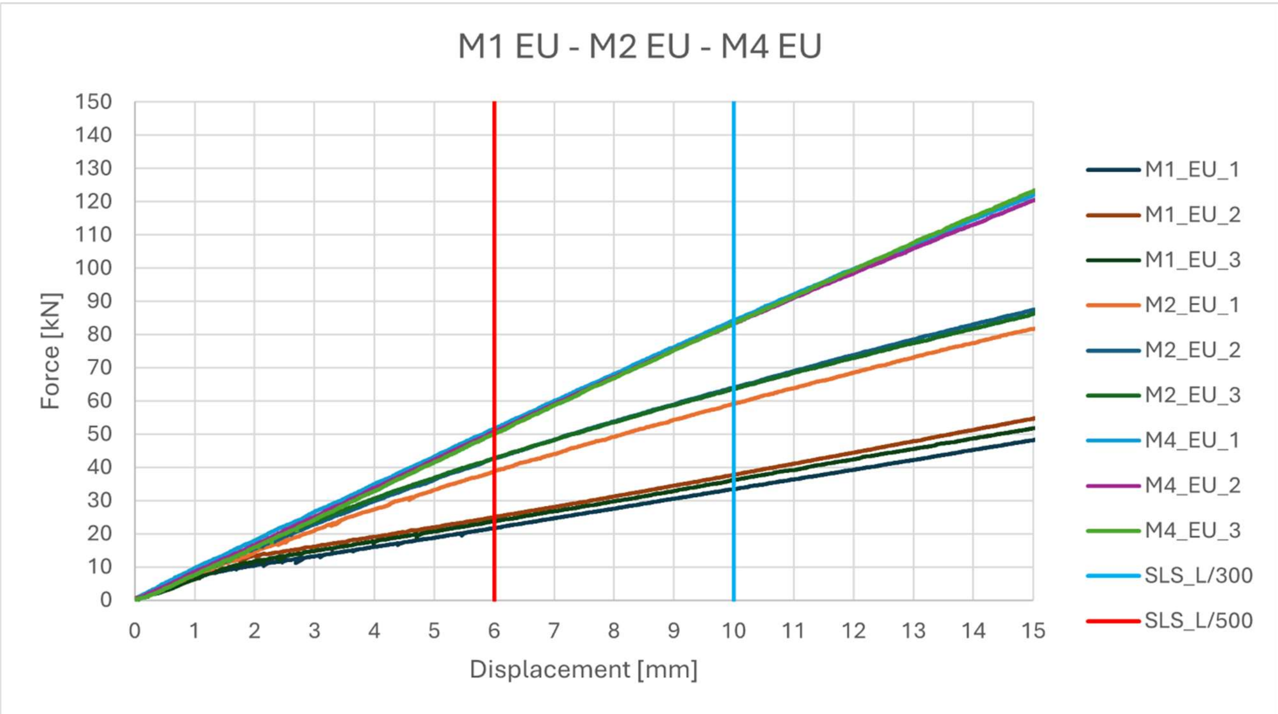
The comparison between the experimental data and the most common serviceability deflection limits prescribed by standards (L/300 for floors with low service requirements and L/500 for floors with normal requirements) highlights which portion of the load–displacement curve is relevant to these evaluations.

By setting the displacement limit, the corresponding load in the pertinent load combination can be derived, i.e., the load level at which that displacement criterion is satisfied.



Picture 39:Comparison - results M1 (screws) - M2 (screws + SHARP METAL)-M4 (screws+glue) – EU timber. The vertical lines indicate two indicative reference values for the SLS.

A qualitative consideration—consistent with expectations—is that the design load increases with the efficiency of the connection. For this reason, a summary table is provided, extracted from the main table presented at the beginning of this section.



Picture 40:Comparison - results M1 (screws) - M2 (screws + SHARP METAL)-M4 (screws+glue) – EU timber. The vertical lines indicate two indicative reference values for the SLS zoom to 15mm.

Name	$F_{l/300}$			$F_{l/300}$ (mean)	$v_{l/300}$
	[kN]			[kN]	[mm]
M1_EU	33,4	37,7	36,0	35.7	10
M2_EU	64,0	64,0	63,6	63.9	
M4_EU	84,2	83,3	83,3	83.6	

Name	$F_{l/500}$			$F_{l/500}$ (mean)	$v_{l/500}$
	[kN]			[kN]	[mm]
M1_EU	21,7	25,0	23,7	23.5	6
M2_EU	42,5	42,6	42,7	42.6	
M4_EU	51,7	50,7	50,0	50.8	

Table 7:Vertical force values corresponding to the maximum displacement values at the SLS (serviceability limit states).

The analysis of these final graphs shows that adopting a mechanical connection system such as SHARP METAL can, for small displacements, achieve a level of efficiency that is sufficient for practical applications with high requirements. The performance of the SHARP METAL system, as indicated by the position of the load–displacement curves, lies in the early loading stages close to the maximum-efficiency curves represented by bonding.
Conversely, the curves corresponding to the solution with screws only are relatively more distant, highlighting a stiffness that is generally insufficient to ensure a high level of composite action between the two elements of the section.

The comparison of the data presented in the previous table highlights the efficiency of the system in achieving a composite section. By comparing the load values corresponding to the beam deflection levels (conventional levels representative of serviceability limit states), the following observations can be made:

- The load value corresponding to the solution with SHARP METAL is approximately 79% higher than that of the solution with screws.
- The load value of the adhesive-based solution is approximately 134% higher than that of the solution with screws.
- When analysing the lowest deflection limit, the following values can be observed:
- The load value of the adhesive-based solution is approximately 116% higher than that of the solution with screws.
- The load value of the SHARP METAL solution is approximately 81% higher than that of the solution with screws.

To assess the reduction in efficiency (in analytical terms) relative to the fully bonded solution, the system using only screws shows a decrease of approximately 54%, while the SHARP METAL system exhibits a reduction of only about 16% compared with the maximum performance achieved through full-surface bonding.

4. MID SCALE CYCLIC TESTS

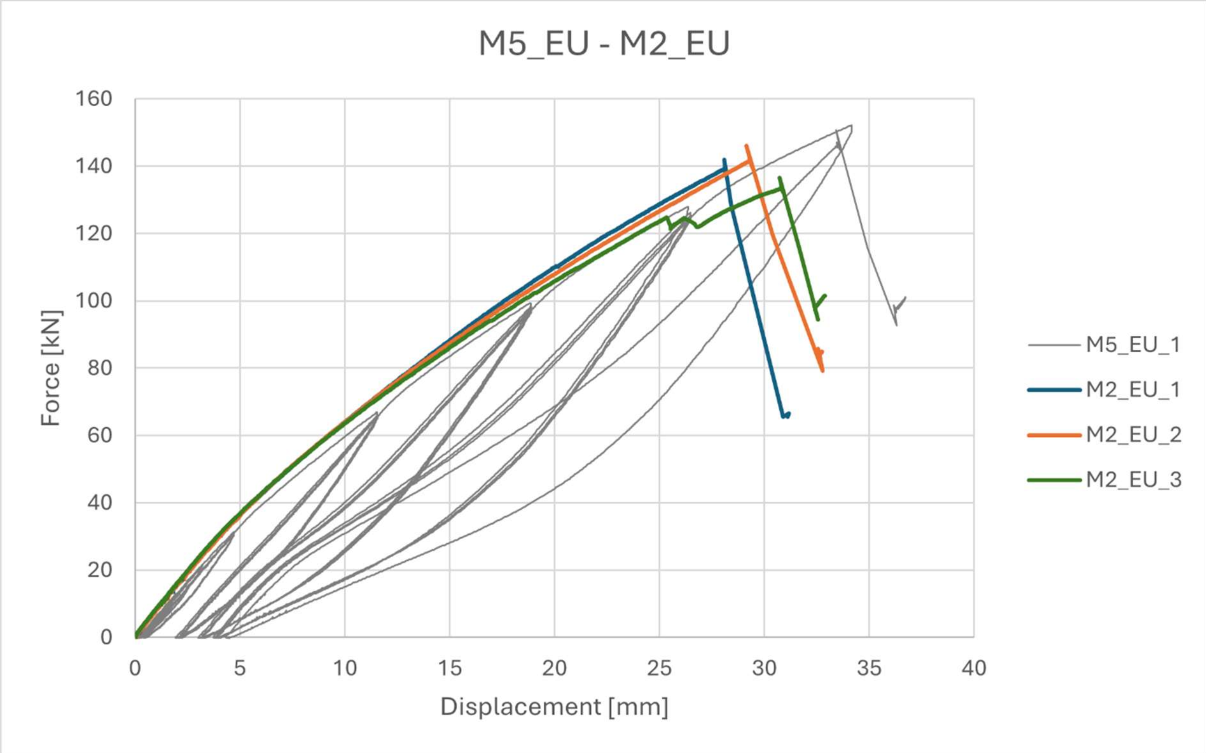
The cyclic tests – or more precisely, the semi-cyclic tests – were carried out on specimens that were geometrically identical to those used in the monotonic tests (M2), both with European timber (EU) and North American timber (SPF).
The imposed displacement was progressively increased up to failure. The protocol reported in the table of the introductory chapter allows correlating each cycle's condition with the corresponding displacement limit relative to the beam length.

Since the specimen was not connected bilaterally to the hydraulic actuator, residual displacements were observed between the loading cycles with higher displacement levels, likely due to residual deformations. This aspect does not affect the overall results of the test and is generally consistent with the condition in which the load is brought back to zero without sign reversal, in order to avoid compensating residual deformations.

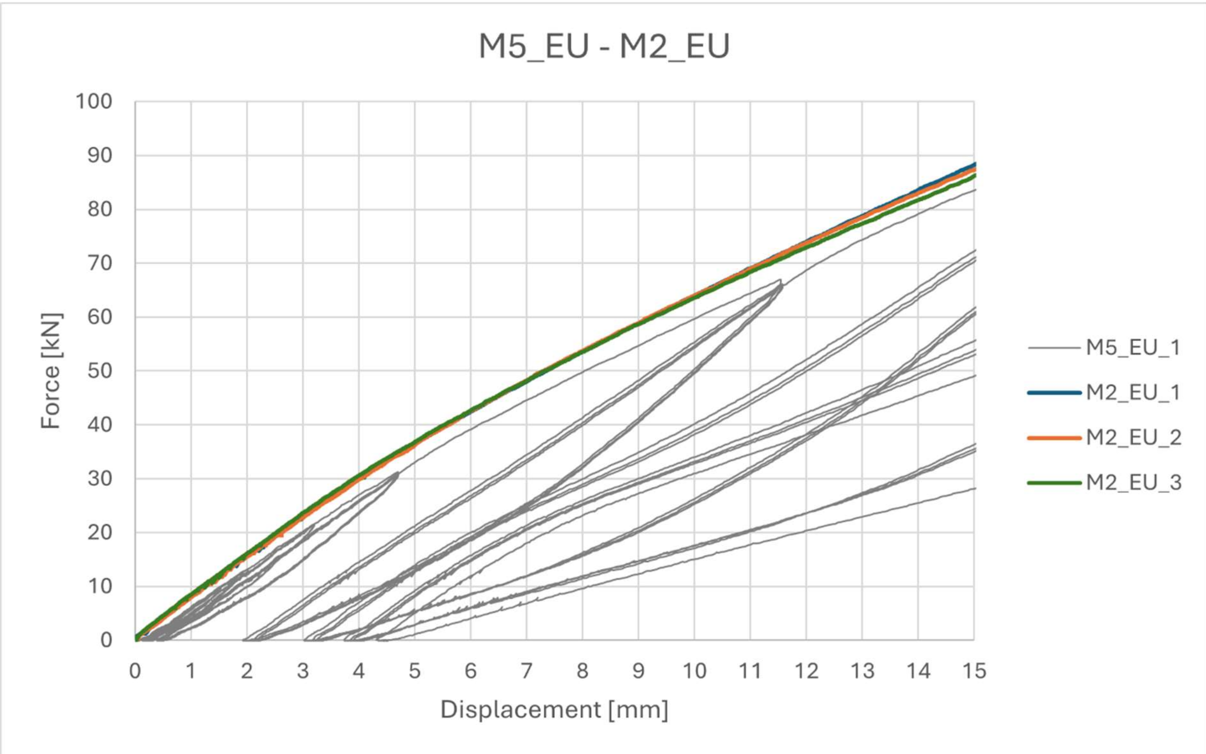
Overall, a smaller degradation is observed at lower displacement levels, with a behaviour largely consistent with the monotonic tests. The variability in the results can be attributed to the heterogeneous nature of timber.

Another notable aspect is the utilisation level of the connection, which does not appear excessively high, given the limited strength degradation between the first and third cycles, even at significant displacement levels.

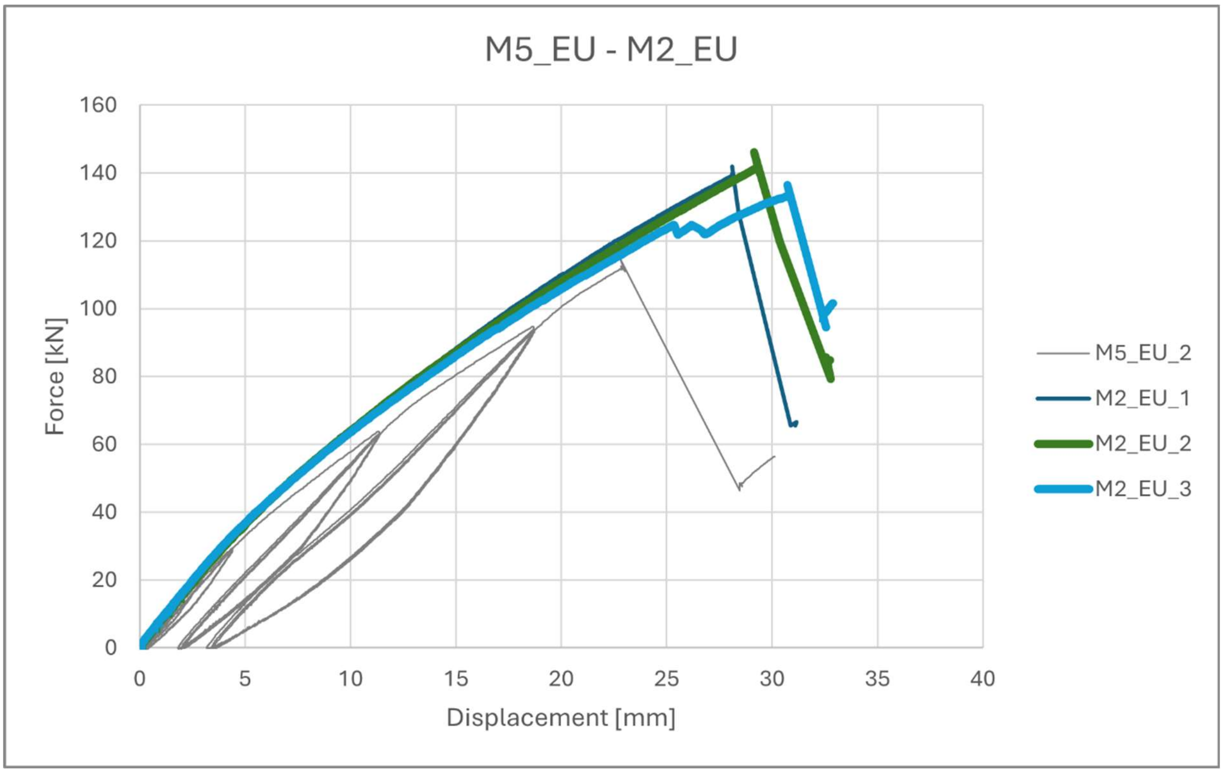
The considerations regarding cyclic behaviour must be interpreted as a comparison between full-scale structural elements tested under equivalent conditions. The relatively high-displacement response observed in the SHARP METAL connection should be contextualised with respect to low-displacement levels.



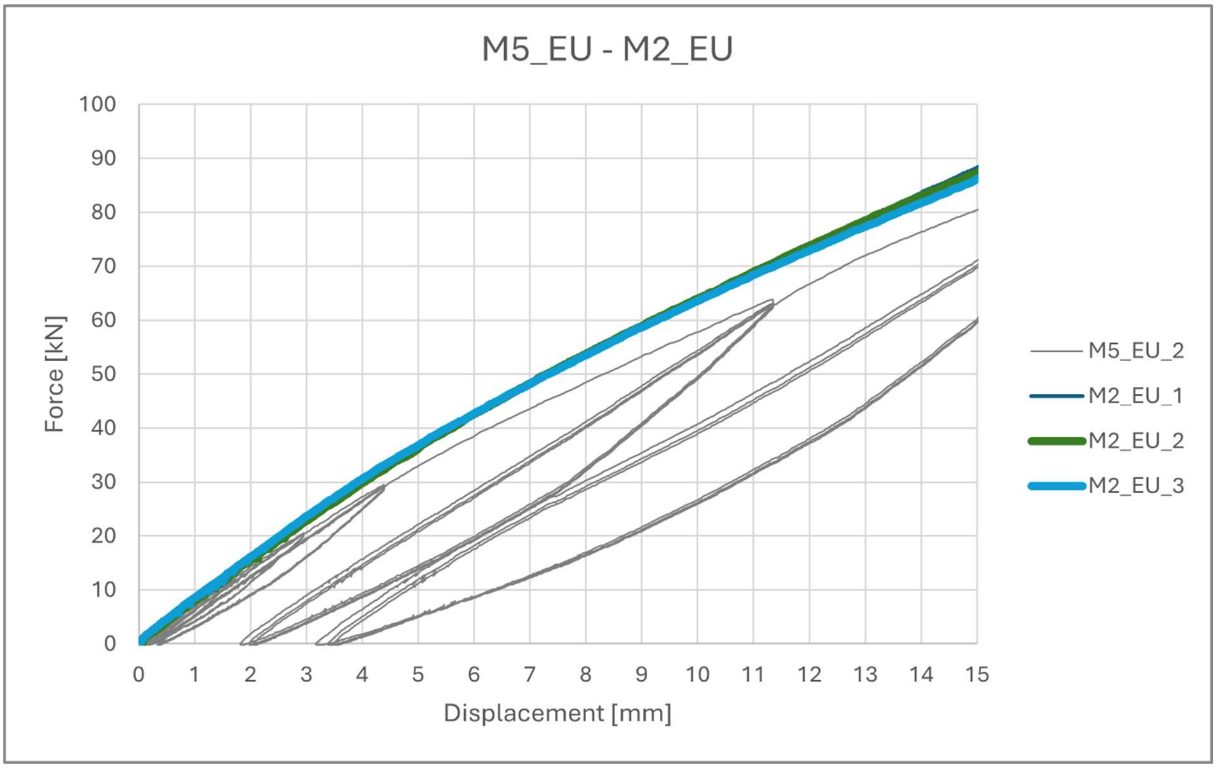
Picture 41: Cyclic test M5_1 (screws + SHARP METAL)- and monotonic tests M2.



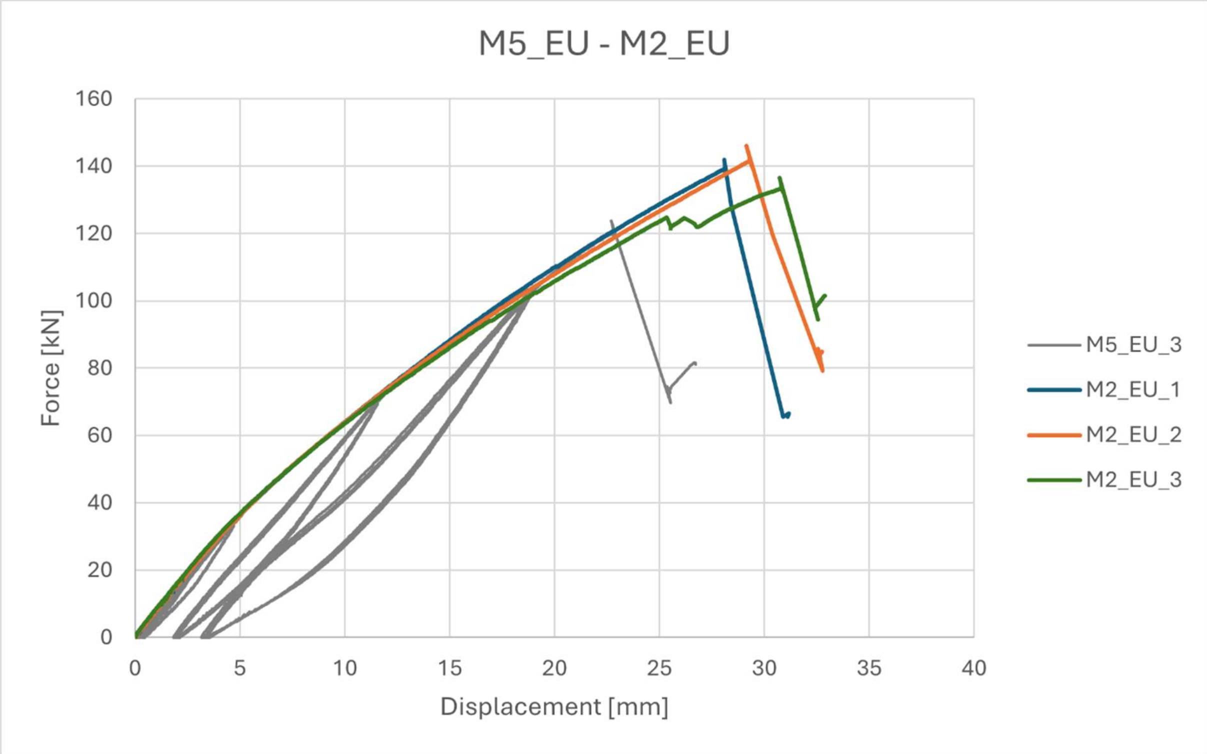
Picture 42: Cyclic test M5_1 (screws + SHARP METAL)- and monotonic tests M2, zoom to 15mm.



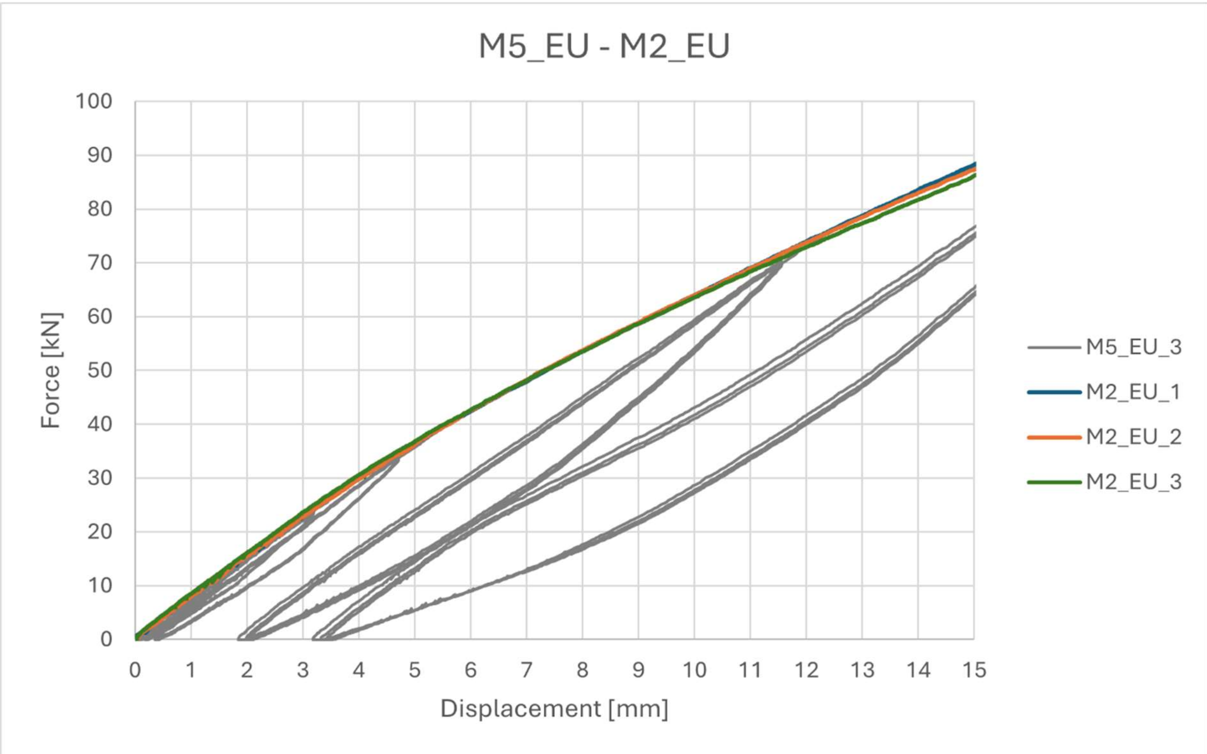
Picture 43: Cyclic test M5_2 (screws + SHARP METAL)- and monotonic tests M2 Eu timber.



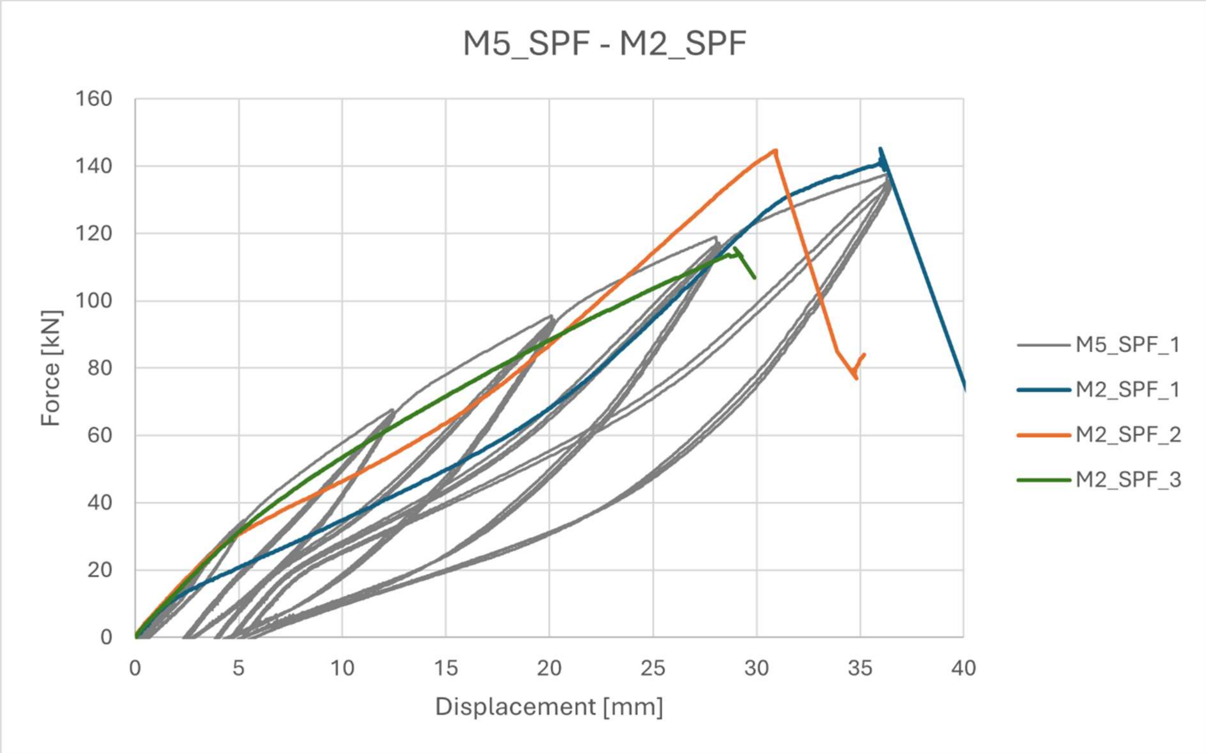
Picture 44: Cyclic test M5_2 (screws+SHARP METAL)-and monotonic tests M2 EU, zoom to 15mm.



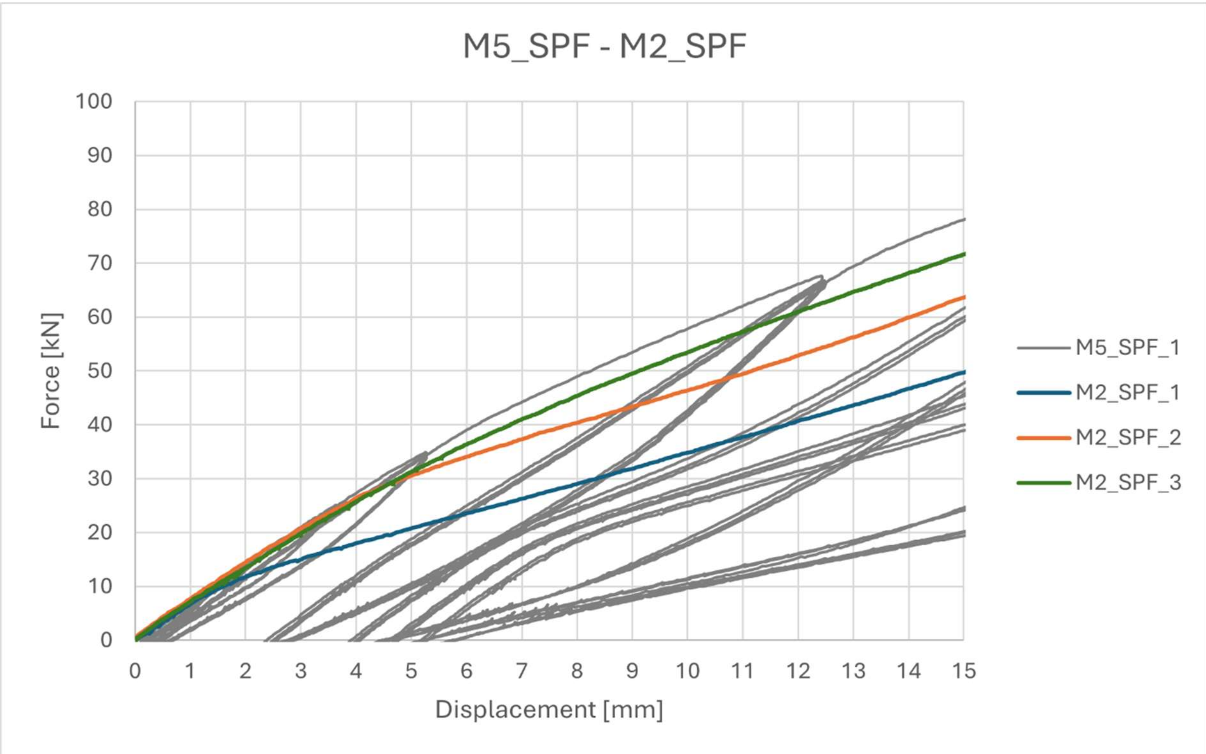
Picture 45:Cyclic test M5_3 (screws + SHARP METAL)- and monotonic tests M2 Eu timber.



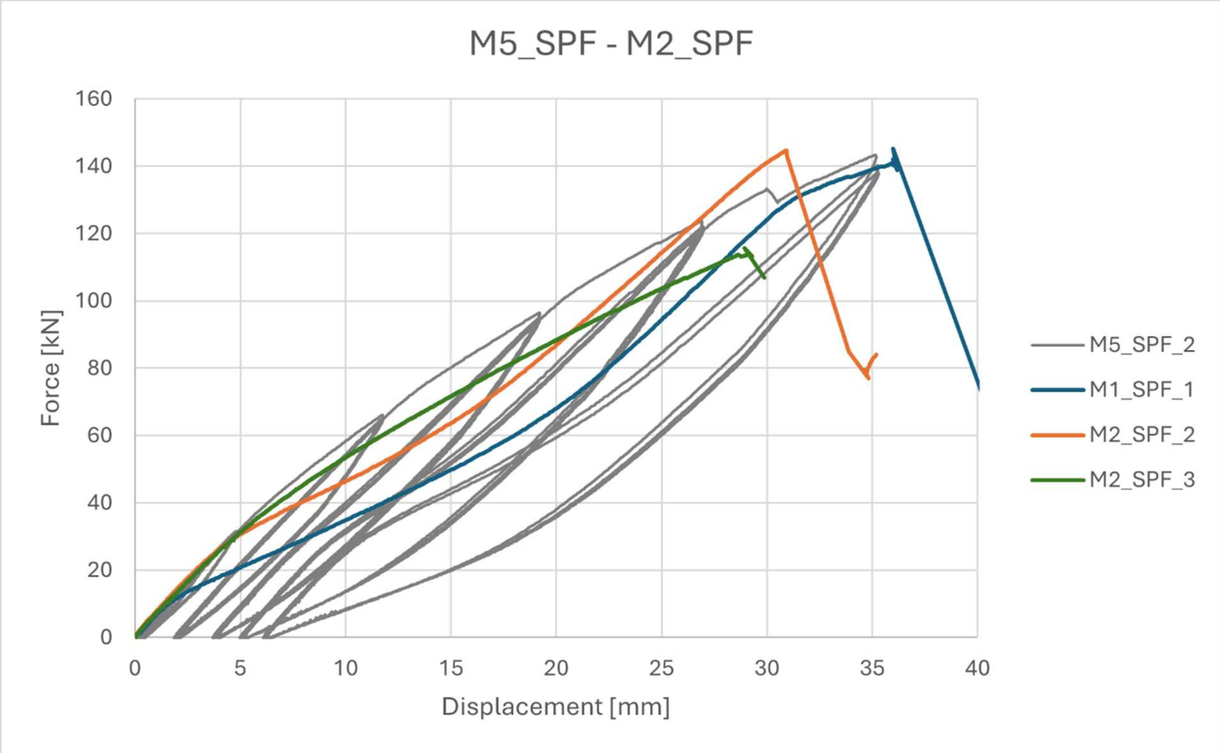
Picture 46: Cyclic test M5_3 (screws + SHARP METAL)-and monotonic tests M2 EU, zoom to 15mm.



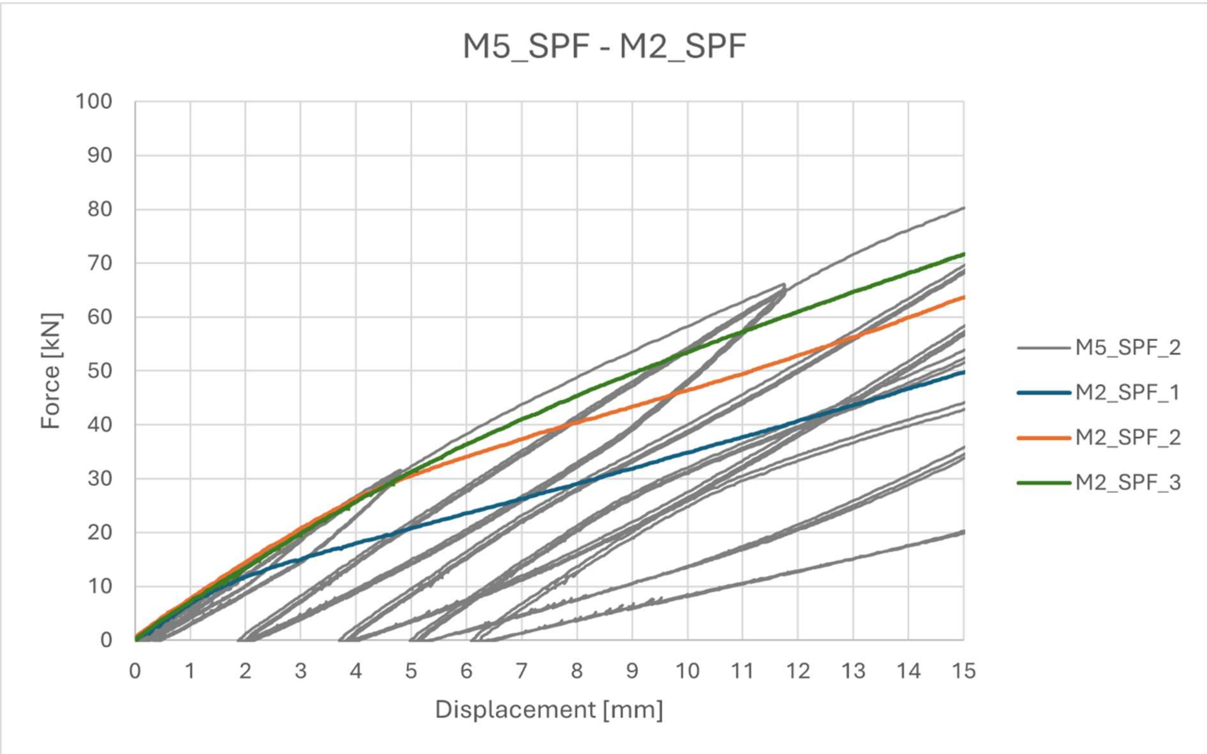
Picture 47: Cyclic test M5_1 (screws + SHARP METAL)- and monotonic tests M2 SPF timber.



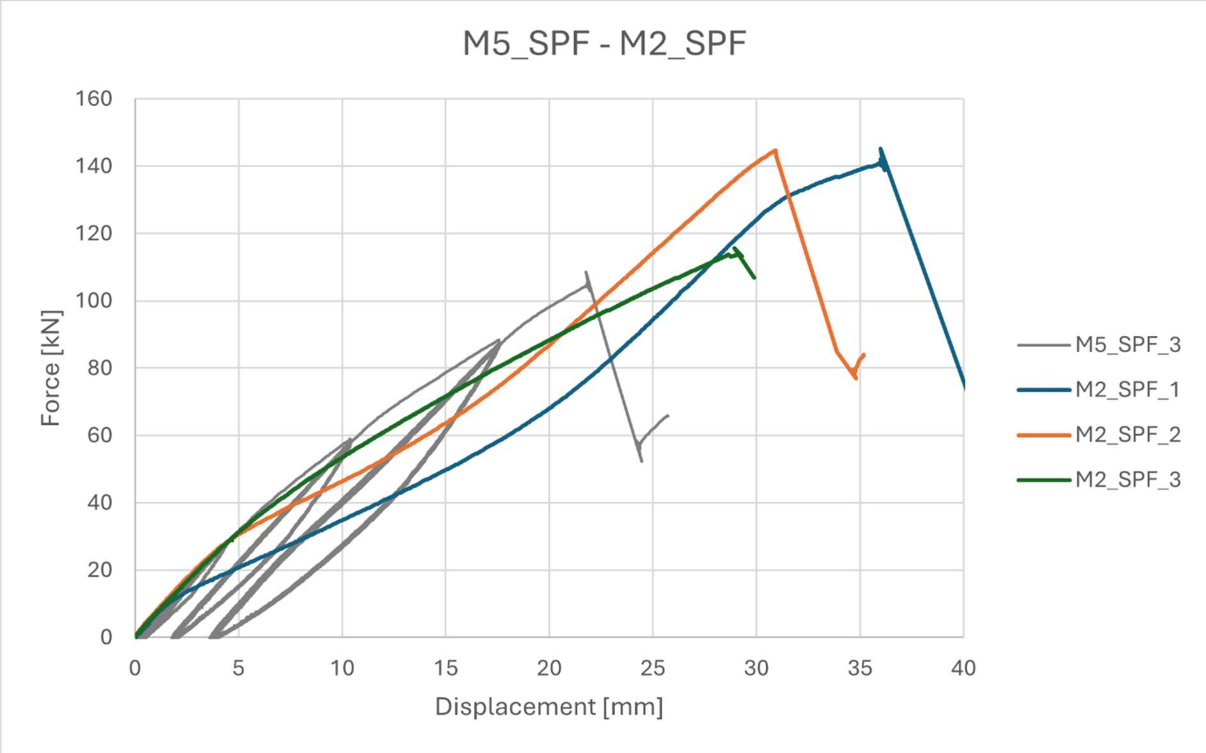
Picture 48: Cyclic test M5_SPF_1 (screws + SHARP METAL)-and monotonic tests M2 SPF, zoom to 15mm.



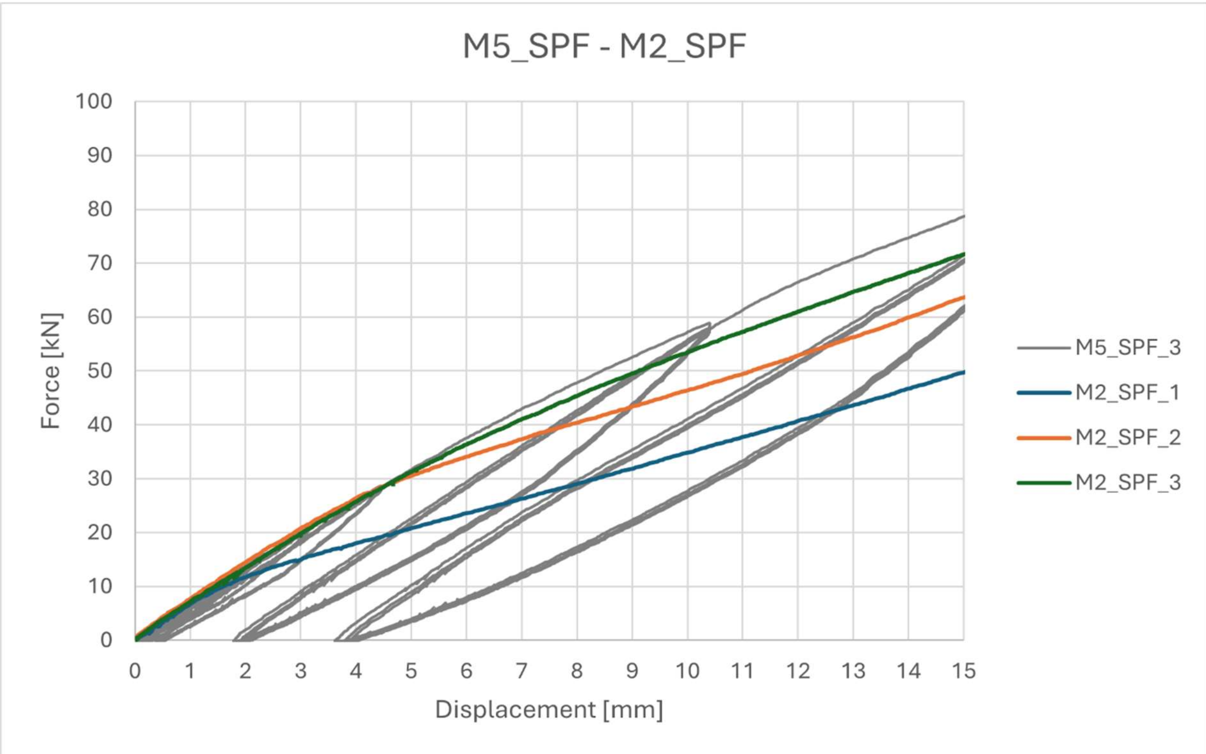
Picture 49:Cyclic test M5_SPF_2 (screws+SHARP METAL)- and monotonic tests M2 SPF timber.



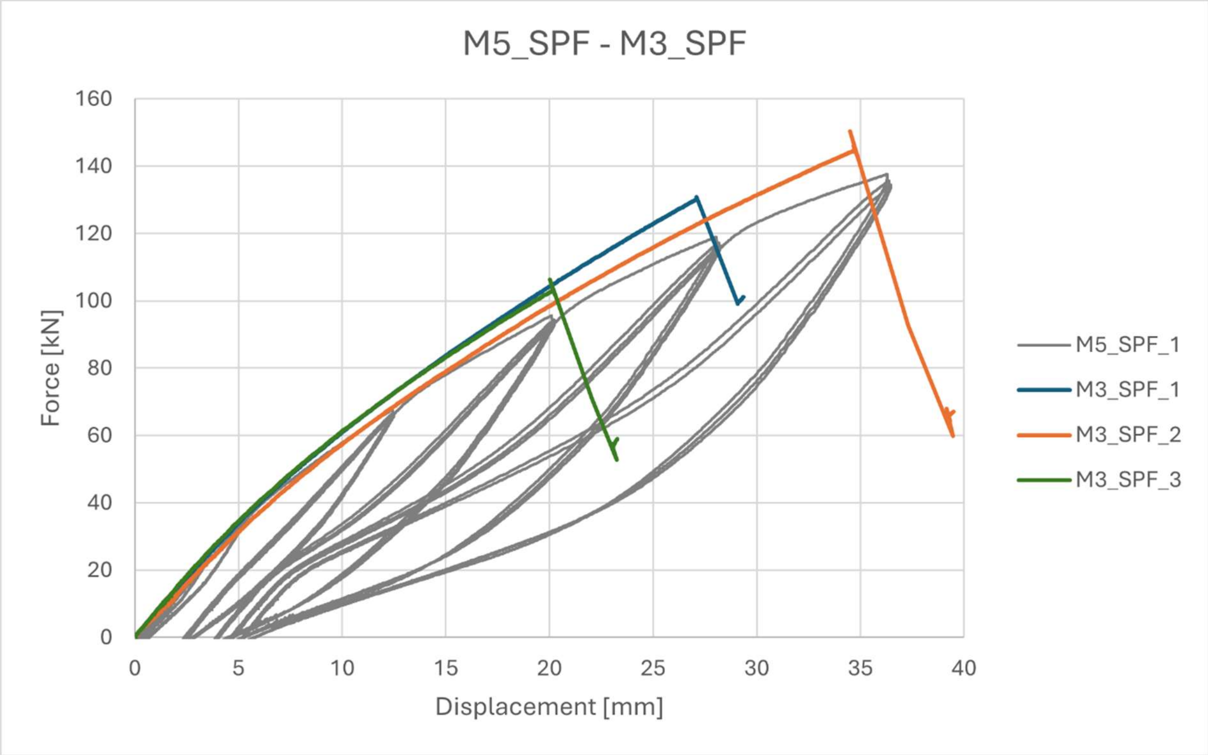
Picture 50: Cyclic test M5_SPF_2 (screws + SHARP METAL)-and monotonic tests M2 SPF, zoom to 15mm.



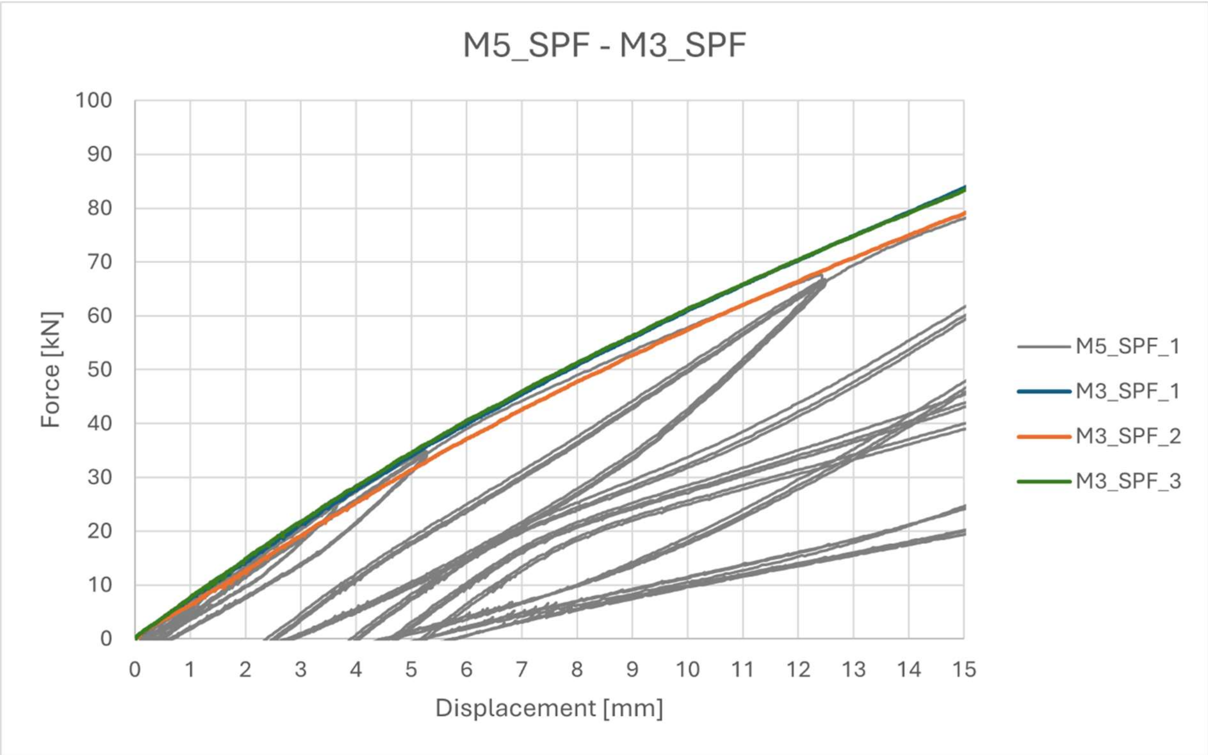
Picture 51:Cyclic test M5_3 (screws+SHARP METAL)- and monotonic tests M2 SPF timber.



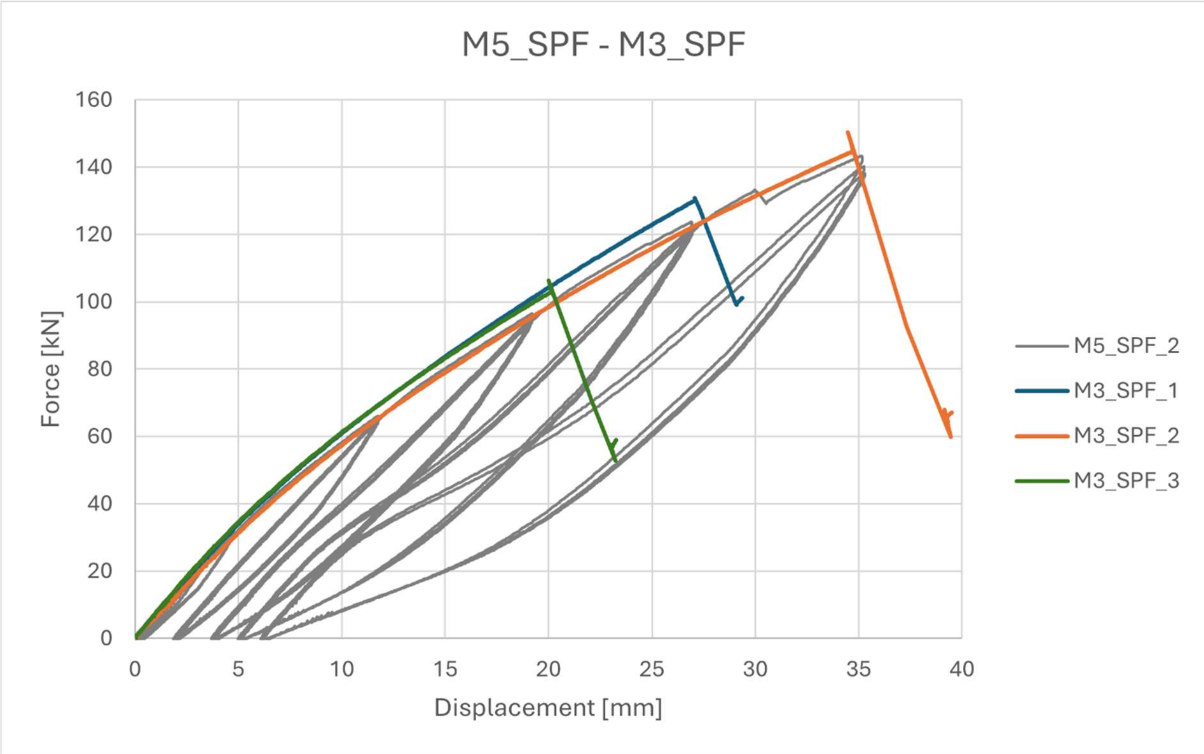
Picture 52: Cyclic test M5_SPF_3 (screws + SHARP METAL)-and monotonic tests M2 SPF, zoom to 15mm.



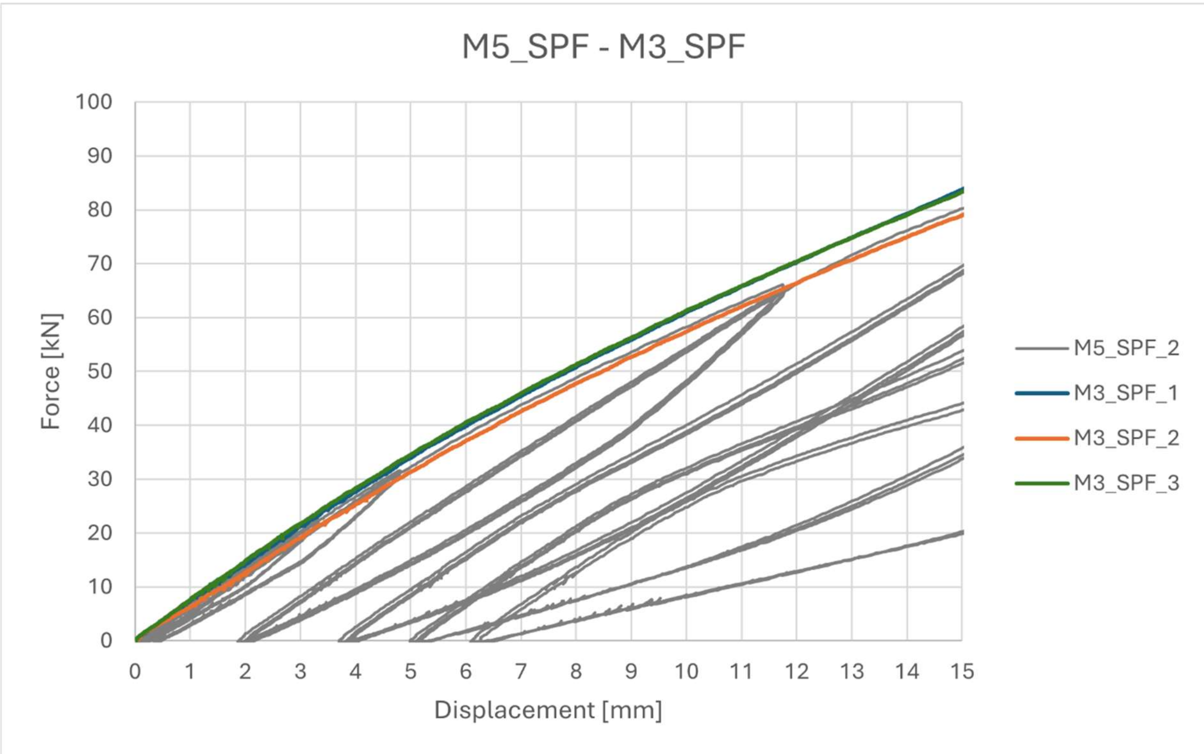
Picture 53:Cyclic test M5_1 (screws+SHARP METAL)- and monotonic tests M3 SPF (with lamination joint) timber.



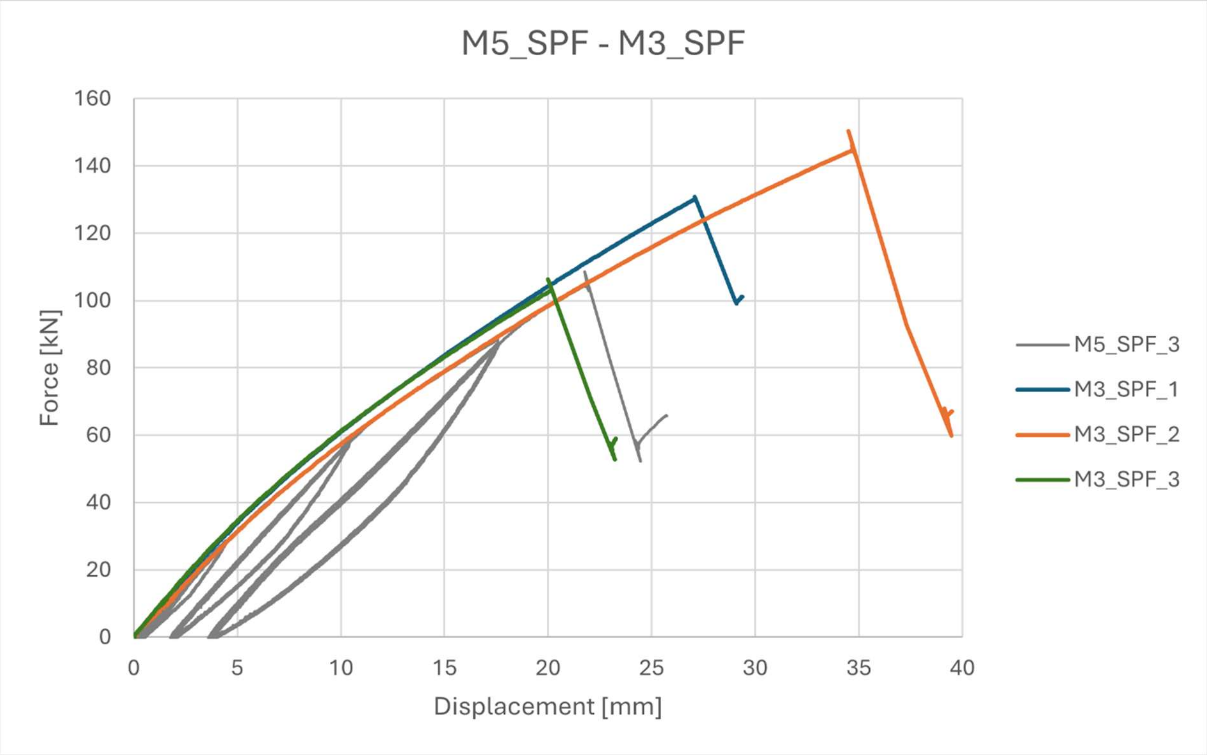
Picture 54: Cyclic test M5_SPF_1 (screws + SHARP METAL)-and monotonic tests M3 SPF, zoom to 15mm.



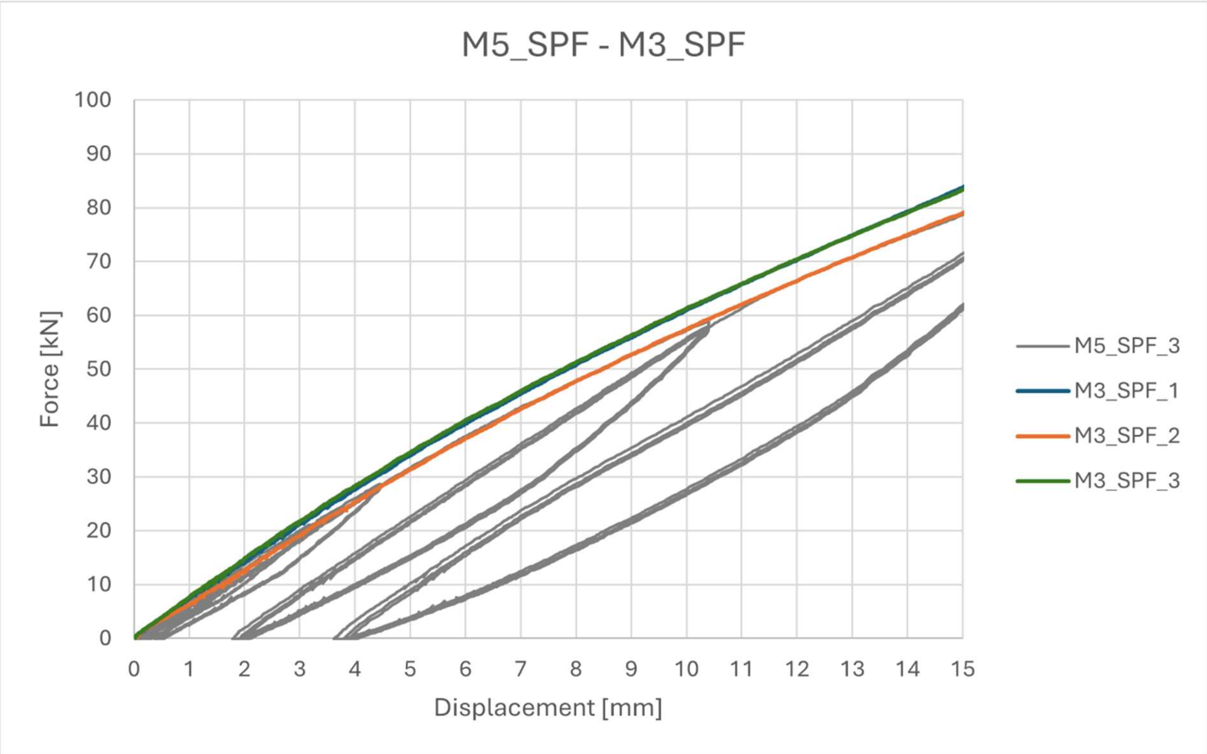
Picture 55:Cyclic test M5_2 (screws + SHARP METAL)- and monotonic tests M3 SPF (with lamination joint) timber.



Picture 56: Cyclic test M5_2 (screws + SHARP METAL)- and monotonic tests M3 SPF (with lamination joint) timber, zoom to15mm.



Picture 57:Cyclic test M5_3 (screws + SHARP METAL)- and monotonic tests M3 SPF (with lamination joint) timber.



Picture 58:Cyclic test M5_3 (screws + SHARP METAL)- and monotonic tests M3 SPF (with lamination joint) timber zoom to 15mm.

END OF THE DOCUMENT

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