Numerical study of the behavior of the bolted shear connection in cold-formed steel-concrete composite beam

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LWT–FLOOR
RESEARCH PROJECT

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Croatian Science Foundation

Outline

- Introduction
- Finite element models
  - Geometry
  - Material properties
  - Boundary and Load Conditions
  - Interactions
- Results
- Conclusions

Introduction

- Sustainability of the built environment (construction industry)
  - ✓ Energy conservation
  - ✓ Conservation of raw material – increase value of structural components and building materials through entire lifecycle

COMPOSITE STEEL-CONCRETE STRUCTURAL SYSTEMS

COLD FORMED STEEL (CFS) SECTIONS

High level of construction efficiency

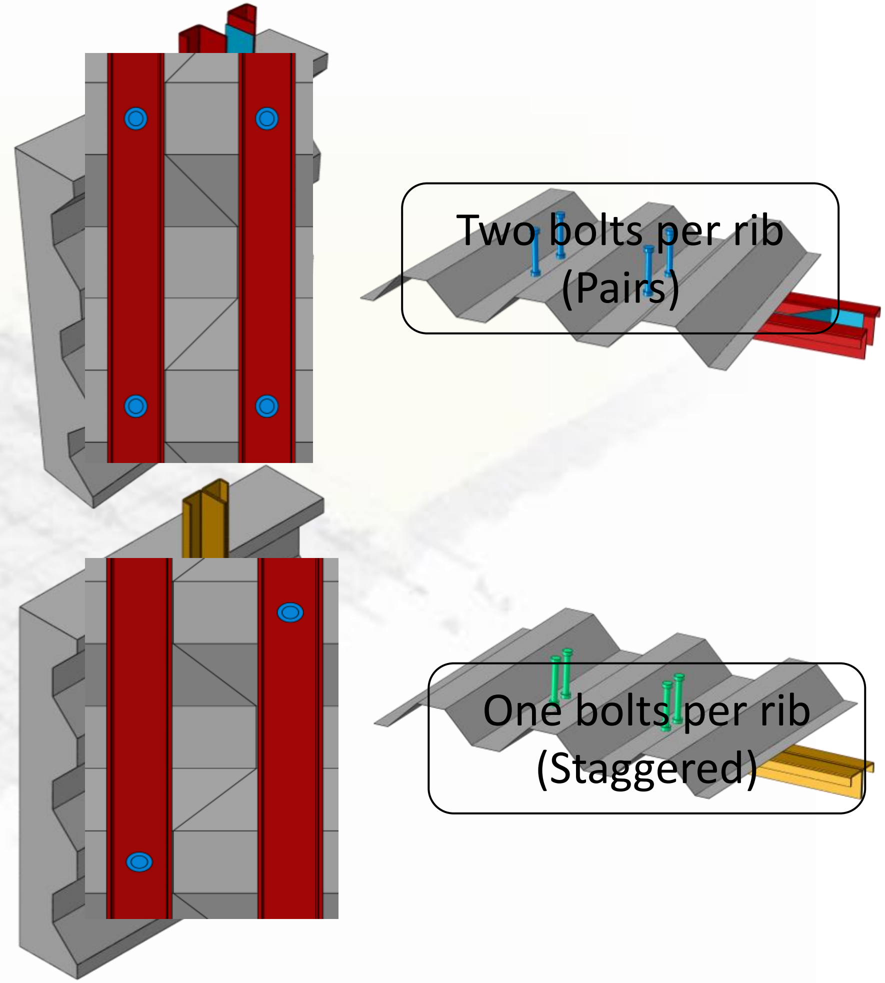
CORRUGATED WEB (CW)

Enable shorter construction times

DEMOUNTABLE SHEAR CONNECTION (SC)

Numerical model - Geometry

- Bolted shear connection (embedded nuts)
  - Embedded nuts
    - ✓ Increased stiffness
    - ✓ Easier mounting
  - Direct shear force transmission
  - M12 and M16, grade 8.8
  - Two bolts positions
    - ✓ Pairs
    - ✓ Staggered
  - CFS thickness 3.0 mm, grade S350GD
  - CW thickness 1.25 mm
  - C20/25 + Q524 mesh

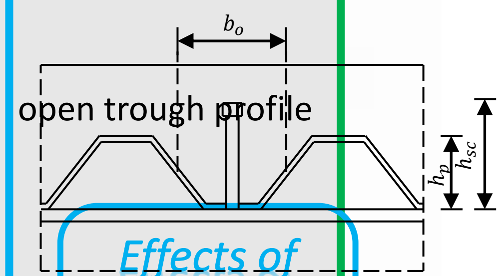


Numerical model - Geometry

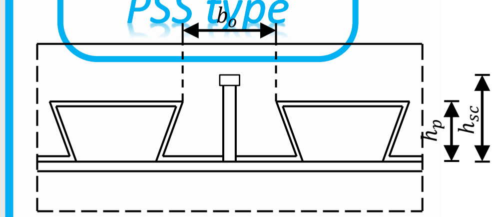
- 24 different models were considered in this study

Model name	Bolts	Bolt position	Profiled steel sheeting [mm] h_p	Profiled steel sheeting [mm] b_o	Concrete class	Corrugated web	Type of PSS
S1_1	M12	Pairs	60	95	C20/25	✓	open trough profile
S1_2	M12	Pairs	60	120	C20/25	✓	open trough profile
S1_3	M12	Pairs	85	90	C20/25	✓	open trough profile
S1_4	M12	Pairs	85	120	C20/25	✓	open trough profile
S2_1	M16	Pairs	60	95	C20/25	✓	open trough profile
S2_2	M16	Pairs	60	120	C20/25	✓	open trough profile
S2_3	M16	Pairs	85	90	C20/25	✓	open trough profile
S2_4	M16	Pairs	85	120	C20/25	✓	open trough profile
S3_1	M12	Pairs	60	95	C20/25	✓	re-entrant trough profile
S3_2	M12	Pairs	60	120	C20/25	✓	re-entrant trough profile
S3_3	M12	Pairs	85	90	C20/25	✓	re-entrant trough profile
S3_4	M12	Pairs	85	120	C20/25	✓	re-entrant trough profile
S4_1	M16	Pairs	60	95	C20/25	✓	re-entrant trough profile
S4_2	M16	Pairs	60	120	C20/25	✓	re-entrant trough profile
S4_3	M16	Pairs	85	90	C20/25	✓	re-entrant trough profile
S4_4	M16	Pairs	85	120	C20/25	✓	re-entrant trough profile

Type of PSS



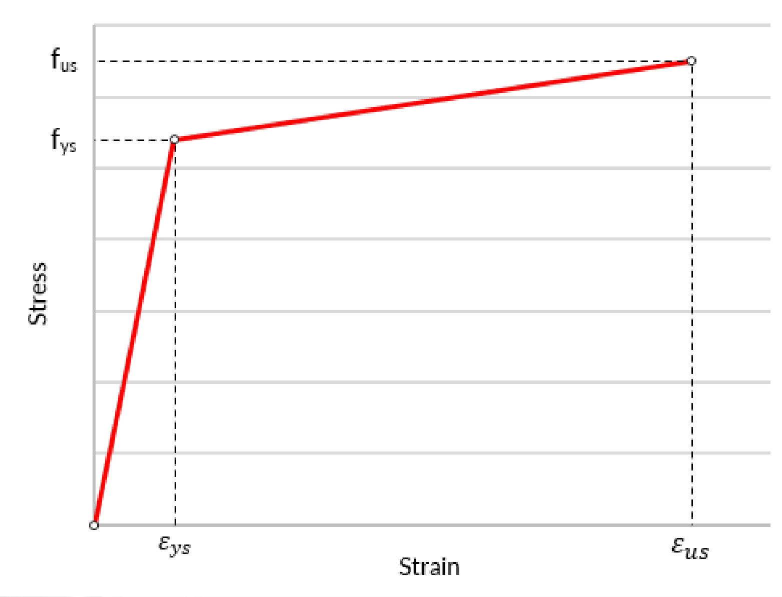
Effects of variation of PSS type



Numerical model- Material properties

- **Steel**
  - Bilinear curve
  - E_s= 210 GPa
  - ν= 0.3
  - ρ= 7850 kg/m^3

Steel	f_{ys} [N/mm²]	f_{us} [N/mm²]	ε_{us} [-]
S350GD	350	420	0.15
8.8	640	800	0.12
Reinforcement	500	500	-



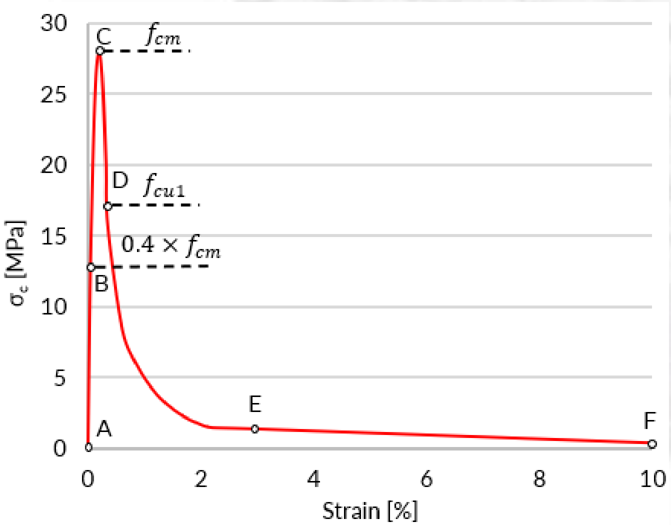
Numerical model- Material properties

- **Concrete**
  - Concrete damage plasticity (CDP) model
  - C20/25 → ρ=2400 kg/m^3
  - Two main failures modes

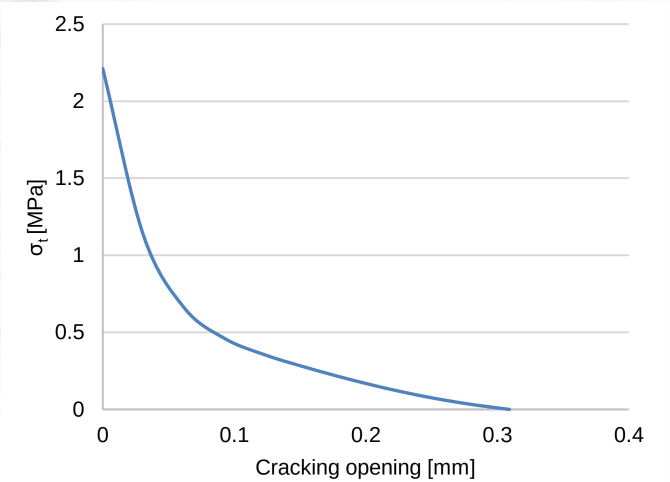
Plastic parameters for CDP model

Dilation angle	Eccentricity	F_{b0}/F_{c0}	K	Viscosity Parameter
31	0.1	1.16	0.667	0.001

Compression failure

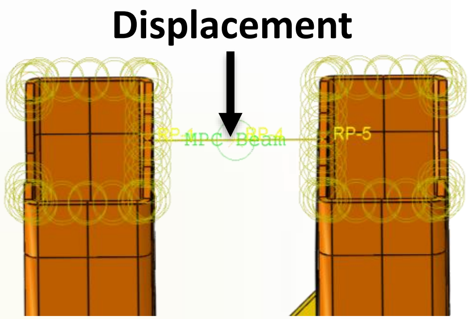


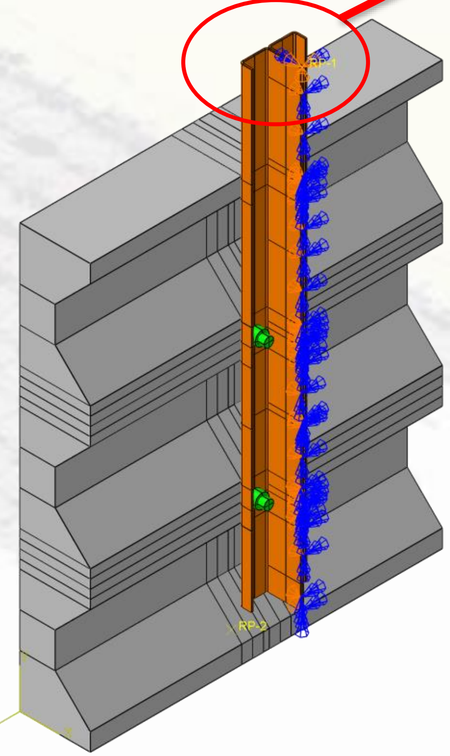
Tension failure

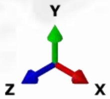


Boundary and Load Conditions

- Boundary Conditions
  - Symmetric boundary conditions
    - ➢ Plane orthogonal to the X-axis
  - Bottom concrete plane
    - ➢ All directions
  - CFS top
    - ➢ Horizontal directions
- Load
  - Displacement: 10 mm
  - Time step: 0.1 s





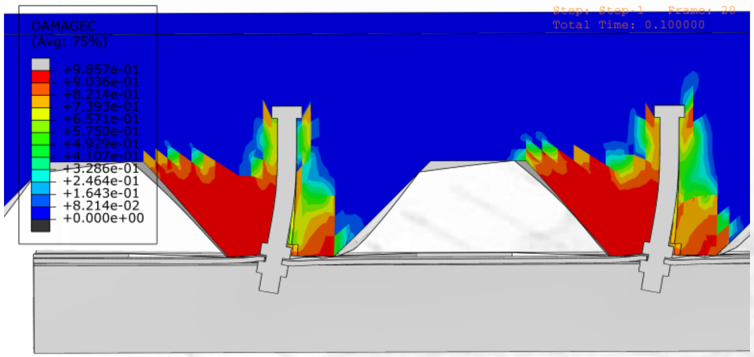


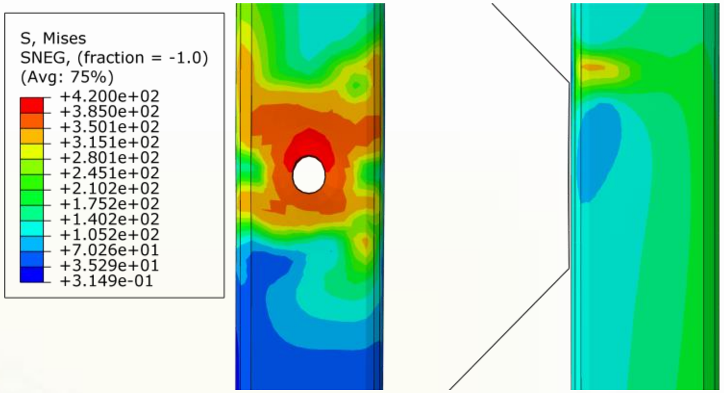
Interactions

- **Surfaces in contact**
  - Normal behaviour
    - Hard contact
  - Tangential behaviour
    - Penalty friction (0.3 frictional coefficient)
- **Spot welds**
  - 3 per CFS profile
  - Rigid behavior (avoid failure)
  - Simulation: MPC Link constraint

Results

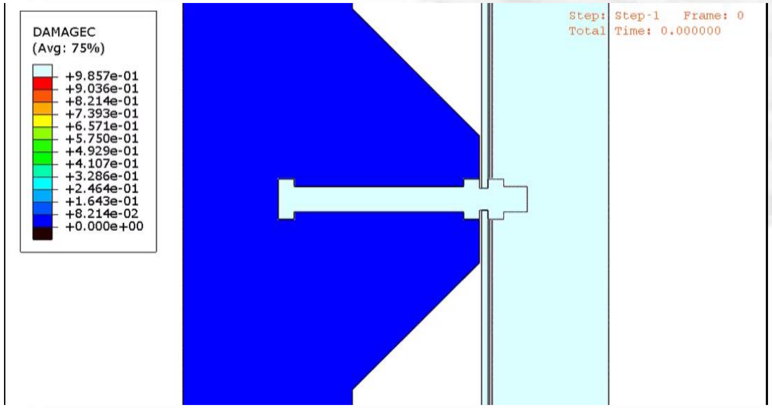
- Failure modes

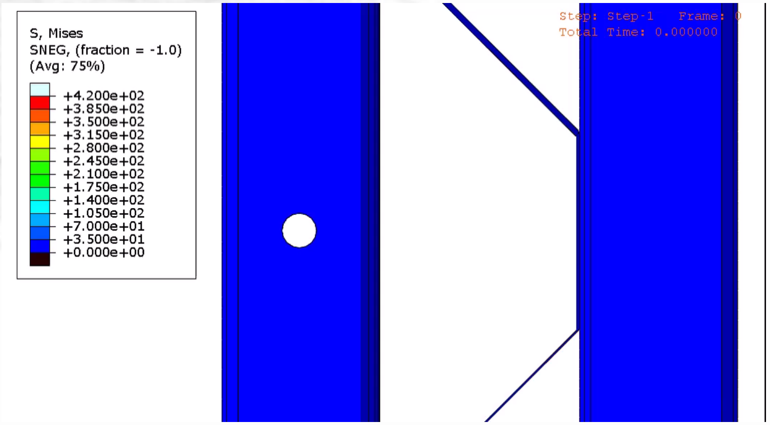




Concrete failure

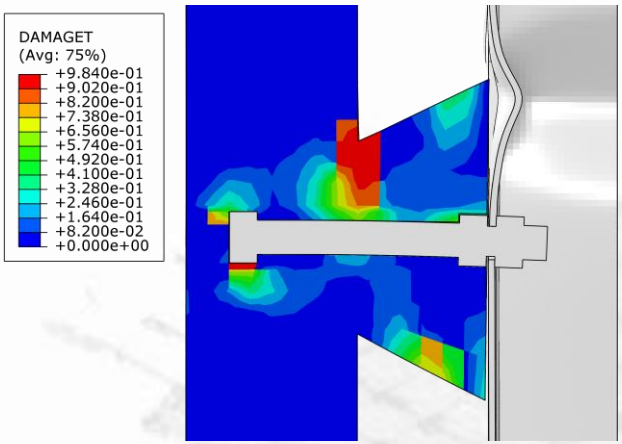
CFS bolt hole bearing resistance

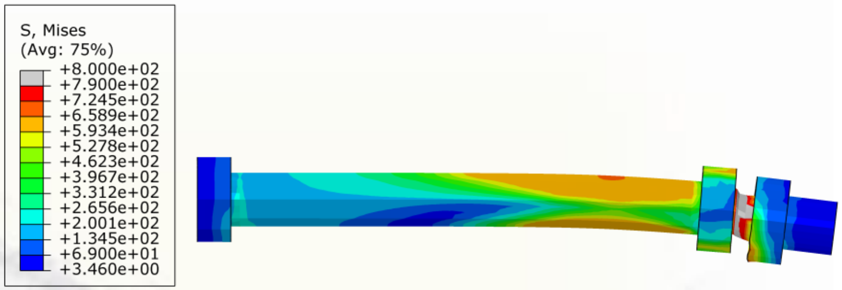




Results

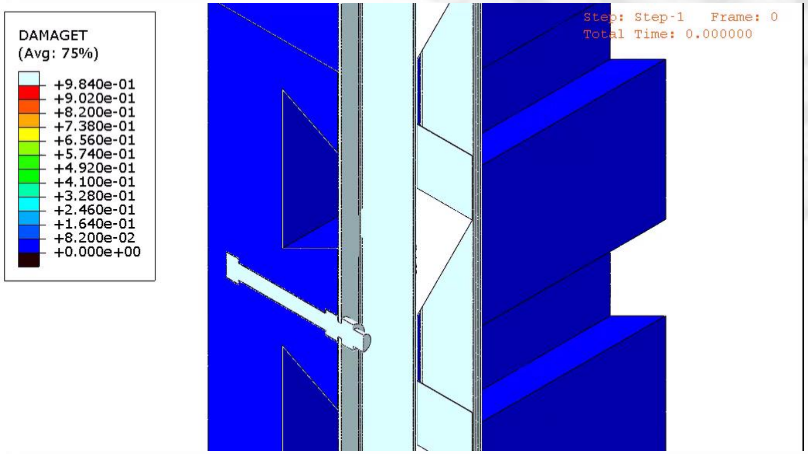
- Failure modes

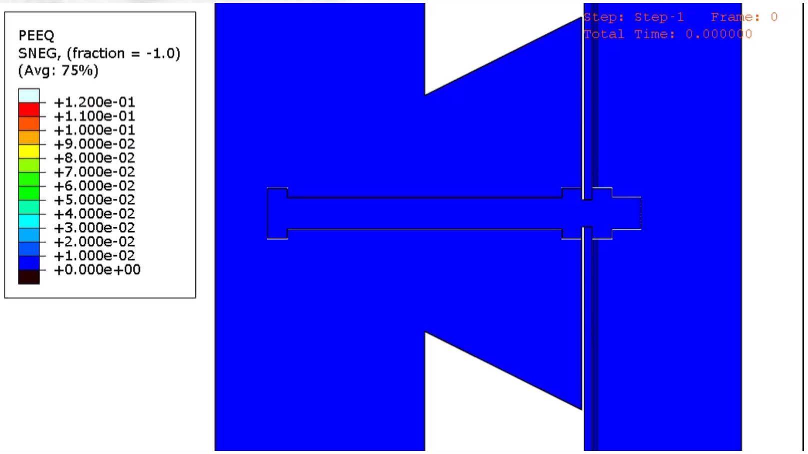




Concrete failure and Stability loss

Shear failure of bolt





- **Effect of variation of connector placement**

$$k_t = \frac{0.7}{\sqrt{n_r}} \frac{b_o}{h_p}\left(\frac{h_{sc}}{h_p} - 1\right)$$

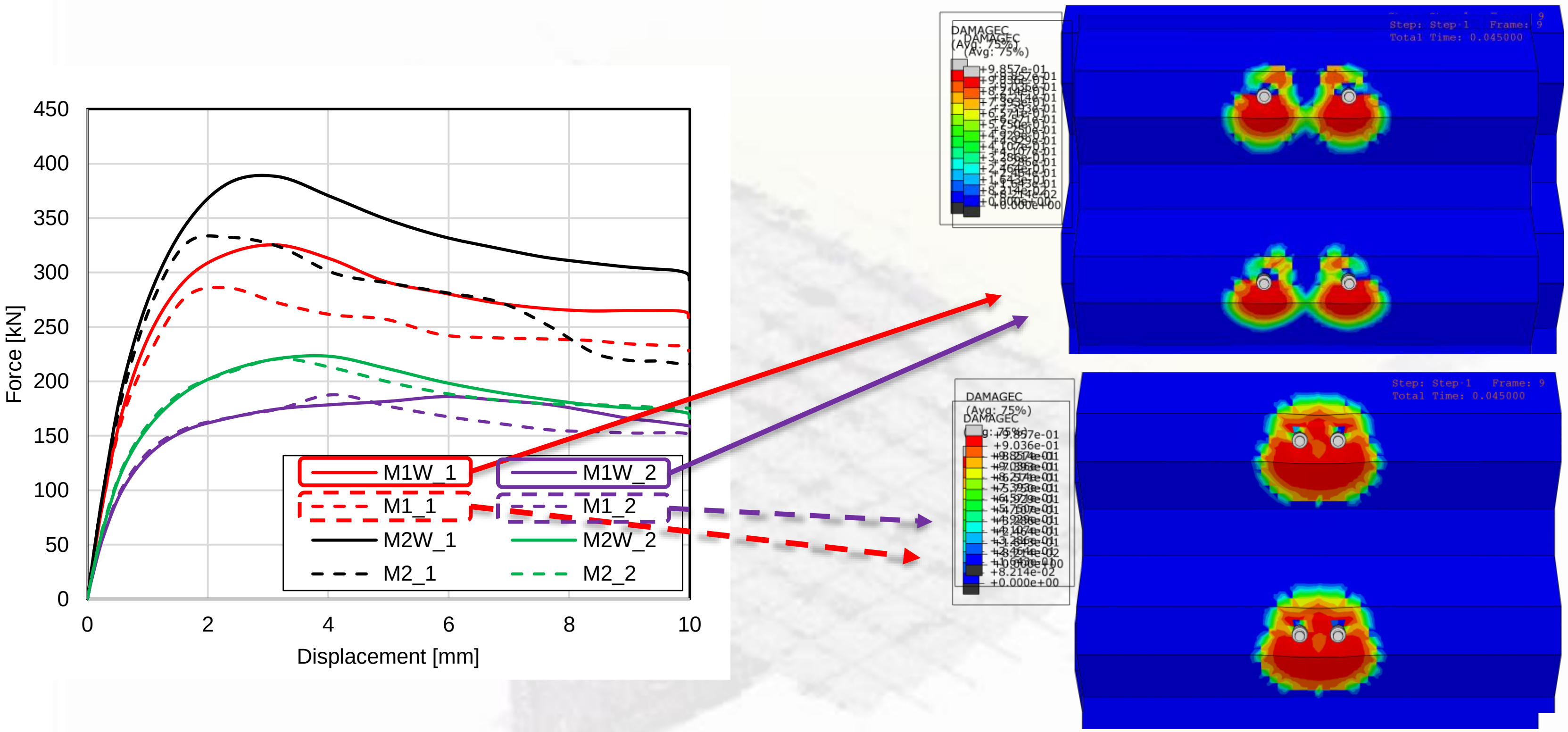
Model name	$F_{b,Rk}$	N_{Rk}	$P_{Rk,S}$	$k_t \cdot P_{Rk,S}$	$P_{Rk,C}$	$k_t \cdot P_{Rk,C}$
M1W_1	32.8	235	54.4	31.6	32.3	18.7
M1W_2				44.1		26.2
M1_1				31.6		18.7
M1_2				44.1		26.2
M2W_1	44.4	235	100	58	57.5	33.4
M2W_2				81		46.6
M2_1				58		33.4
M2_2				81		46.6

Single connector or element

Two bolts per rib
$k_t = 0.58$
One bolt per rib
$k_t = 0.81$

Results

- **Effect of variation of connector placement**



- **Effect of variation of connector placement**

Bolts of smaller diamater (M12)

Model name	F_{NUM}	Failure mode	F_{CALC}	$\frac{F_{CALC}}{F_{NUM}}$	$k_t \cdot F_{CALC}$	$\frac{k_t \cdot F_{CALC}}{F_{NUM}}$
M1W_1	324	Concrete	258	0.80	149.6	0.46
M1W_2	186	Concrete	129	0.70	105	0.56
M1_1	286	Concrete	258	0.90	149.6	0.52
M1_2	188	Concrete	129	0.70	105	0.56
M2W_1	388	Concrete	460	1.19	268	0.70
M2W_2	224	Concrete	230	1.03	186	0.83
M2_1	332	Concrete	460	1.39	268	0.81
M2_2	220	Concrete	230	1.05	186	0.85

Whole model

Results

- **Effect of variation of PSS type**

Model name	$F_{b,Rk}$	$F_{v,Rk}$	N_{Rk}	$P_{Rk,S}$	$P_{Rk,C}$	k_t	k_{t,up_limits}	$k_t \cdot P_{Rk,S}$	$k_t \cdot P_{Rk,C}$
S1_1 / S3_1	32.8	162	235	54.4	32.3	0.74	0.70	38.1	22.61
S1_2 / S3_2	32.8	162	235	54.4	32.3	0.99	0.70	38.1	22.61
S1_3 / S3_3	32.8	162	235	54.4	32.3	0.22		12	7.11
S1_4 / S3_4	32.8	162	235	54.4	32.3	0.29		15.81	9.37
S2_1 / S4_1	44.4	302	235	100	57.5	0.74	0.70	70	40.25
S2_2 / S4_2	44.4	302	235	100	57.5	0.99	0.70	70	40.25
S2_3 / S4_3	44.4	302	235	100	57.5	0.22		22	12.65
S2_4 / S4_4	44.4	302	235	100	57.5	0.29		29	16.68

Single connector or element

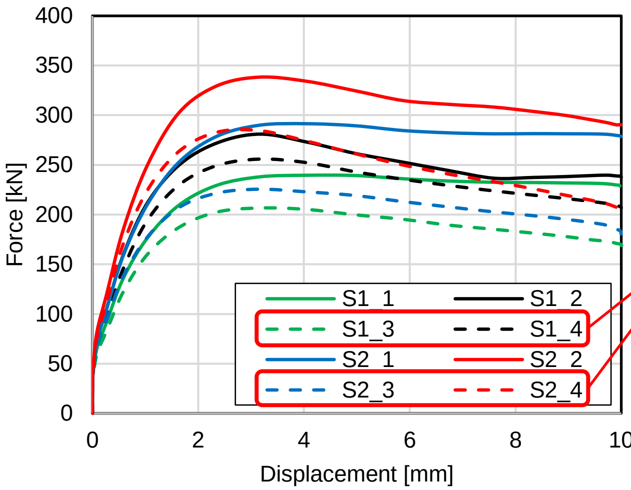
- **Effect of variation of PSS type**

Model name	F_{NUM}	Failure mode	F_{CALC}	F_{CALC}/F_{NUM}	$k_t \cdot F_{CALC}$	$k_t \cdot F_{CALC}/F_{NUM}$
S1_1	240	C.C.	258	1.07	181	0.75
S1_2	281	C.C.	258	0.92	181	0.64
S1_3	207	C.C.	258	1.24	56.8	0.27
S1_4	256	C.C.	258	1.01	74.8	0.29
S2_1	293	C.C.	460	1.57	322	1.09
S2_2	339	C.C.	460	1.35	322	0.95
S2_3	226	C.C.	460	2.04	102	0.38
S2_4	285	C.C.	460	1.61	133	0.46
S3_1	376	S.B.	324	0.86	-	-
S3_2	376	S.B.	324	0.86	-	-
S3_3	260	C.C.	258	0.99	56.8	0.22
S3_4	332	C.C.	258	0.78	74.8	0.23
S4_1	392	C.C/S.	460	1.18	322	0.82
S4_2	411	C.C/S.	460	1.12	322	0.78
S4_3	281	C.C.	460	1.63	102	0.36
S4_4	328	C.C.	460	1.40	133	0.41

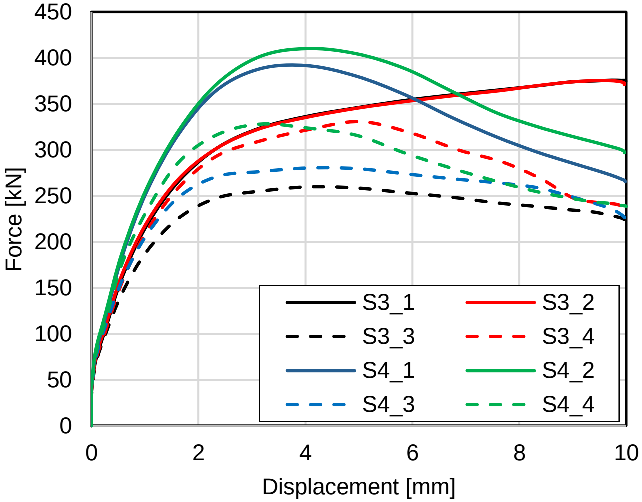
Whole models

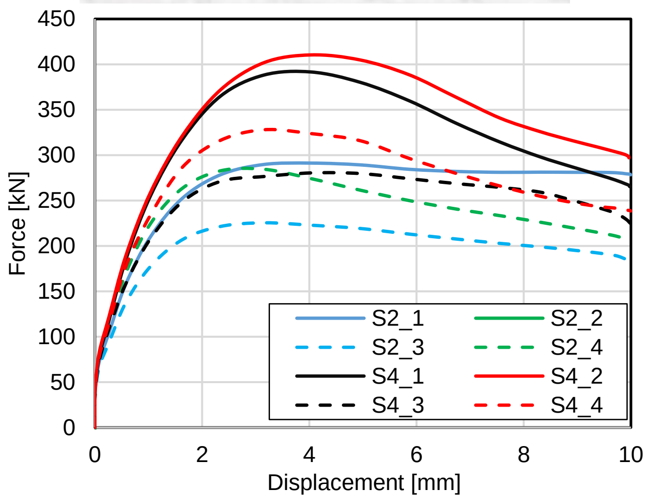
Note: C.C.= concrete slab cracking; S.B.= Bolt shear failure; S.= CFS C profile stability loss

- **Effect of variation of PSS type**



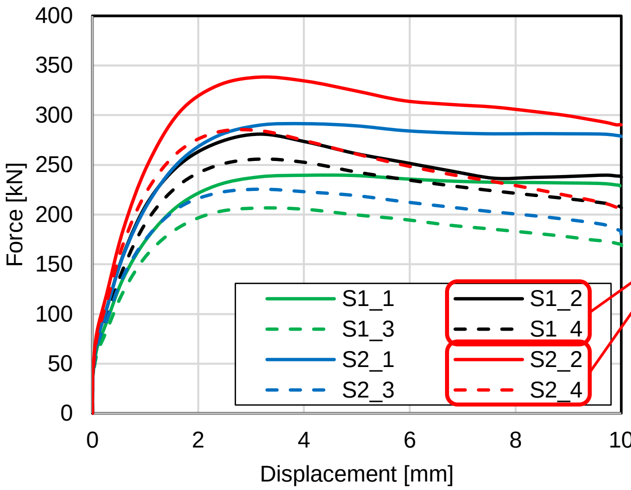
Increasing the height of the rib = Lower resistance of the model



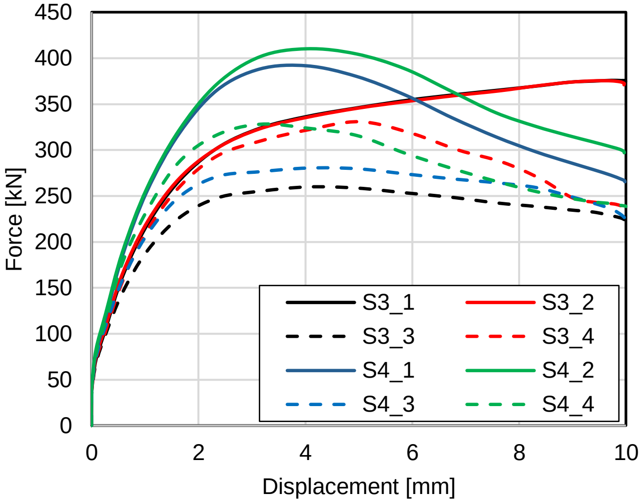


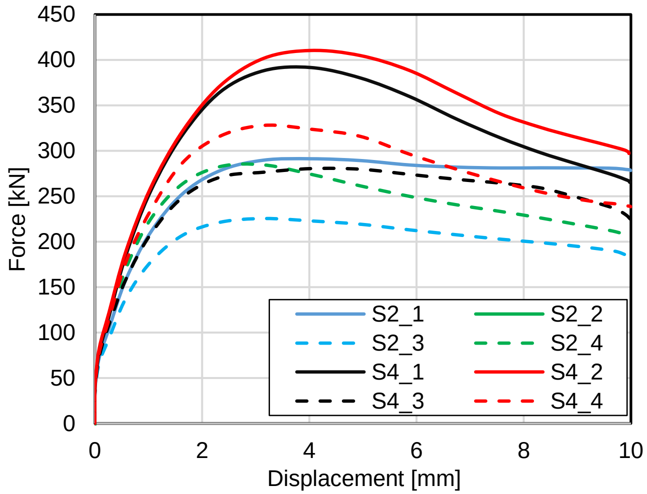
Results

- **Effect of variation of PSS type**



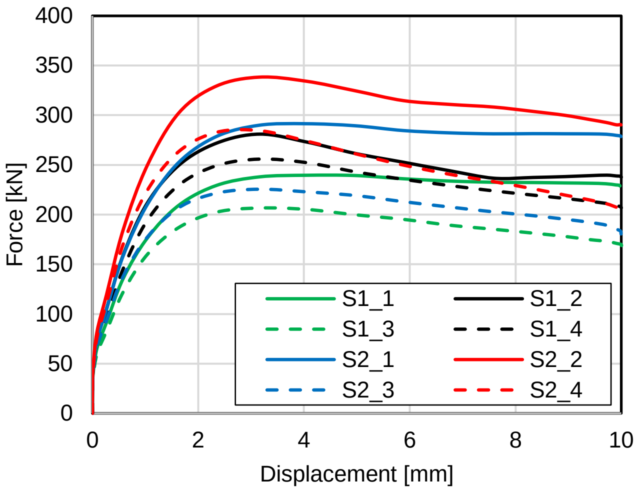
Wider PSS ribs = Higher resistance of shear connectors in concrete

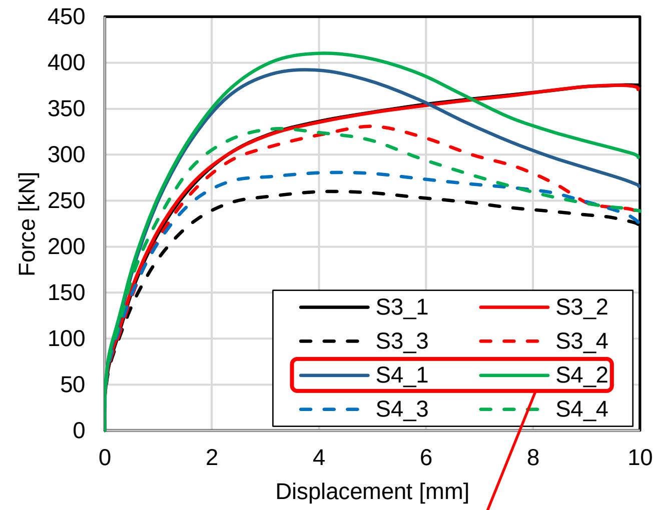


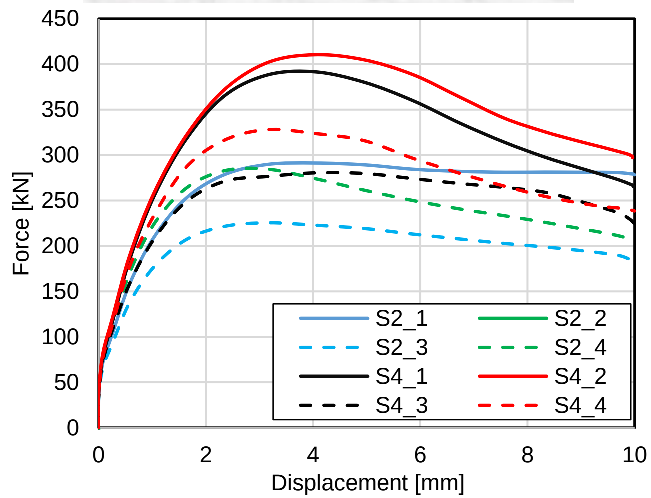


Results

- **Effect of variation of PSS type**







Combined failure mode:
Concrete failure
Loss of stability of the CFS profile

Conclusions

- The distance between the shear connectors in the rib of the concrete slab affects on the resistance of the model. Also the resistance of the shear connection may depends on the position of the bolt in the rib.
- Influence of bolt diameter on the shear connection failure in concrete when ribs are transverse to the beam should be checked. There is indication that the reduction factor, $\mathbf{k_t}$ might be increased or even completely omitted for smaller bolt diameters
- Application of the reduction factor, k_t should be checked for strengths **>450 MPa**, and bolts with diameter **<16 mm**
- Changing the type of PSS from the one with open troughs to the one with re-entrant troughs resulted in greater resistance with similar stiffness and ductility. Also the geometry of the PSS results in different failure modes

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