

Project title: Innovative lightweight cold-formed steel-concrete composite floor system

Acronym: LWT-FLOOR Project ID: UIP-2020-02-2964

5th LWT-FLOOR Project Workshop, Zagreb, 18th-19th December 2025

RELIABILITY OF SHEAR CONNECTION IN COLD-FORMED STEEL-CONCRETE COMPOSITE SYSTEM

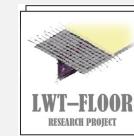
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<http://www.grad.unizg.hr/lwtfloor>

Acknowledgment



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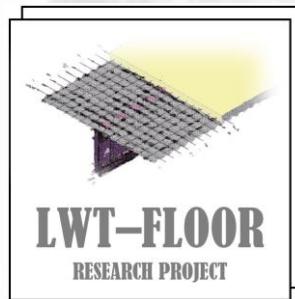


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- Suggest directions for future research

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1. Introduction

1. Introduction

Problems

Current situation

- Composite steel-concrete structures widely used
- Steel tensile strength + concrete compressive strength
- Welded studs are standard shear connectors
- Focus on fast, sustainable, reusable construction
- Cold-formed steel (CFS) used for lightweight, efficient systems



Connection

Welded studs
non-dismountable
↓
limited reuse



Material

Concrete
production
↓
high CO₂ impact



Sustainability

Need demountable
connections
↓
faster and recyclable
construction



Steel

CFS prone to buckling → limited research on innovative shapes

Study objectives



Step 1

Review of existing literature



Step 2

Experimental investigation



Step 3

Numerical modelling



Step 4

Numerical parametric analysis and
development of an analytical method



Step 5

Probabilistic assessment of analytical
method

Two hypotheses

Hypothesis

01

The demountable shear connection ensures a reliable connection between the cold-formed steel sections and the reinforced concrete slab of the composite system.

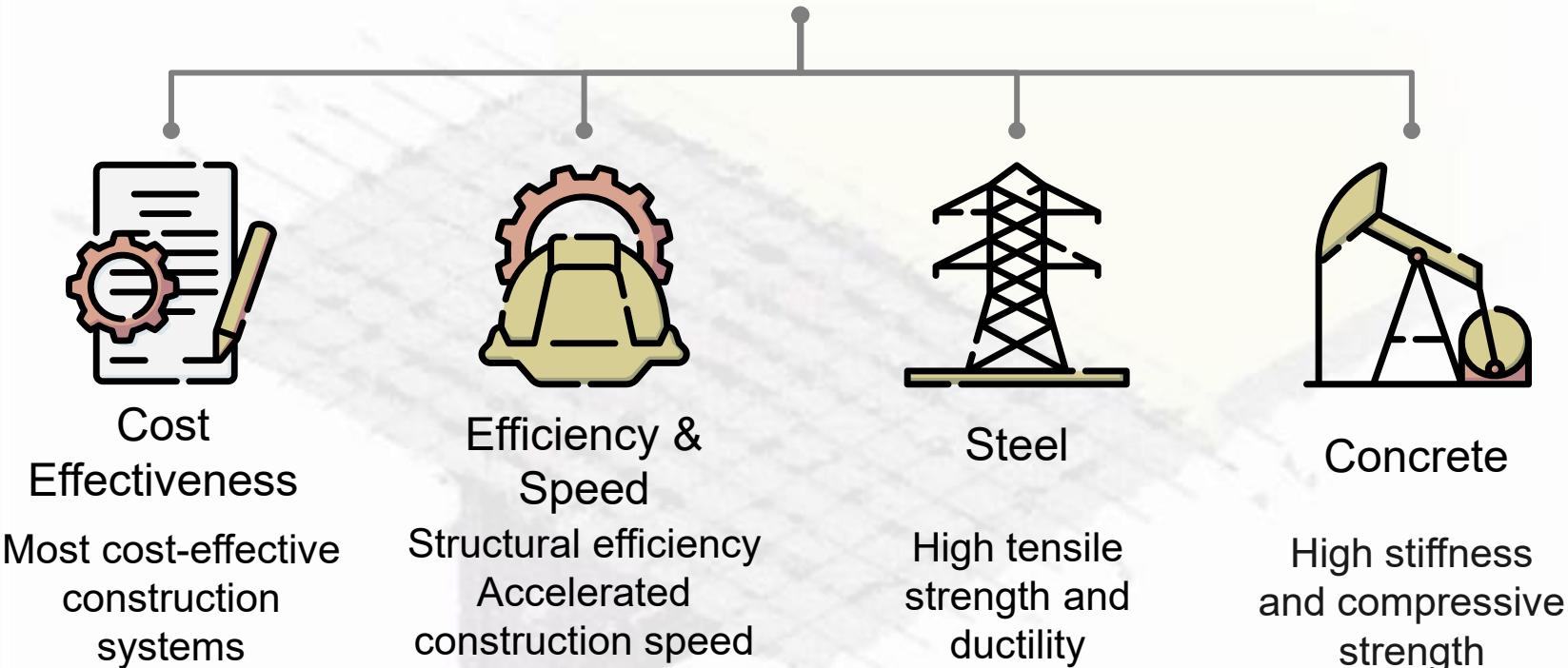
02 Hypothesis

Application of lightweight and normalweight concrete within the considered system allows achievement of similar resistance and ductility of the shear connection.

2. Literature review

2. Literature review

Composite steel-concrete structural systems



2. Literature review

Composite built-up cold-formed steel girders (CFS) with a corrugated web and concrete slab

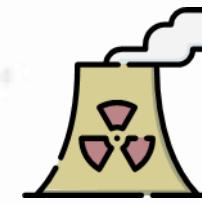
Continuous Development

Composite steel-concrete systems remain a field of continuous development.



Material Efficiency

Growing tendency to reduce material usage while enhancing performance



2. Literature review

Authors, years	Type of shear connection	Parameters	Key findings
Hawkins, N.M. et al., 1984	Welded headed studs	Diameter of welded studs and type of the concrete slab	Four primary failure modes
Johnson, R.P. et al., 1998	Welded headed studs	Type of the concrete slab	Five different failure modes
Dallam, L.N. et al., 1968	Friction grip bolts	Bolt diameter	2 × shear capacity of welded studs
Ataei, A. et al., 2016	Friction grip bolts	Embedded and post-installed bolts	Different behaviour in monolithic and precast slabs
Dai, X.H. et al., 2015-2017	Threaded headed studs	Size of the shear stud collar, thread length, concrete strength and reinforcement layout	Lower stiffness, higher ductility and comparable shear capacity compared to welded studs
Pavlović, M. et al., 2013, 2017	Bolts with embedded nuts	Bolt preloading force, number of embedded nuts, longitudinal spacing, concrete class and height-diameter ratio	Two primary failure mechanisms. 95% of the shear resistance of traditional welded studs
Shamel Fahmy, A. et al., 2023	Bolts with embedded nuts	Grout strength, height-diameter ratio, bolt material and preloading force	Ratio < 5 leads to concrete crushing, while > 5 causes bolt failure

2. Literature review

Authors, years	Type of shear connection	Parameters	Key findings
Hosseinpour, M. et al., 2021-2022	Bolts with embedded nuts	Thickness of the CFS section, diameter and strength of the bolts	Thin CFS: thickness & strength; thick CFS: thickness, bolt size & concrete strength
Ataei, A. et al., 2023-2024	Bolts with embedded nuts	Thickness of the CFS section, diameter and strength of the bolts, concrete class and pretension force	Thin specimens → distortional buckling of CFS Thick specimens → connector failure
Salah, M.S. et al., 2023	Bolts with embedded nuts	Bolt diameter and CFS beam cross-section	Cross-section of the CFS beam does not influence the failure mode
Rahnavard, R. et al., 2023	Bolts with embedded nuts	Full scale profiled composite beam	Revealed structural vulnerabilities
Shakarami, M. et al., 2023	Friction grip bolts	Thickness of the CFS section, diameter and strength of the bolts	Thin CFS: bolt hole bearing; thick CFS: bearing + bolt shear.
Hanaor, A., 2000	Embedded and dry solution	Different types of the shear connection	High ductility and adaptability in cross-section design

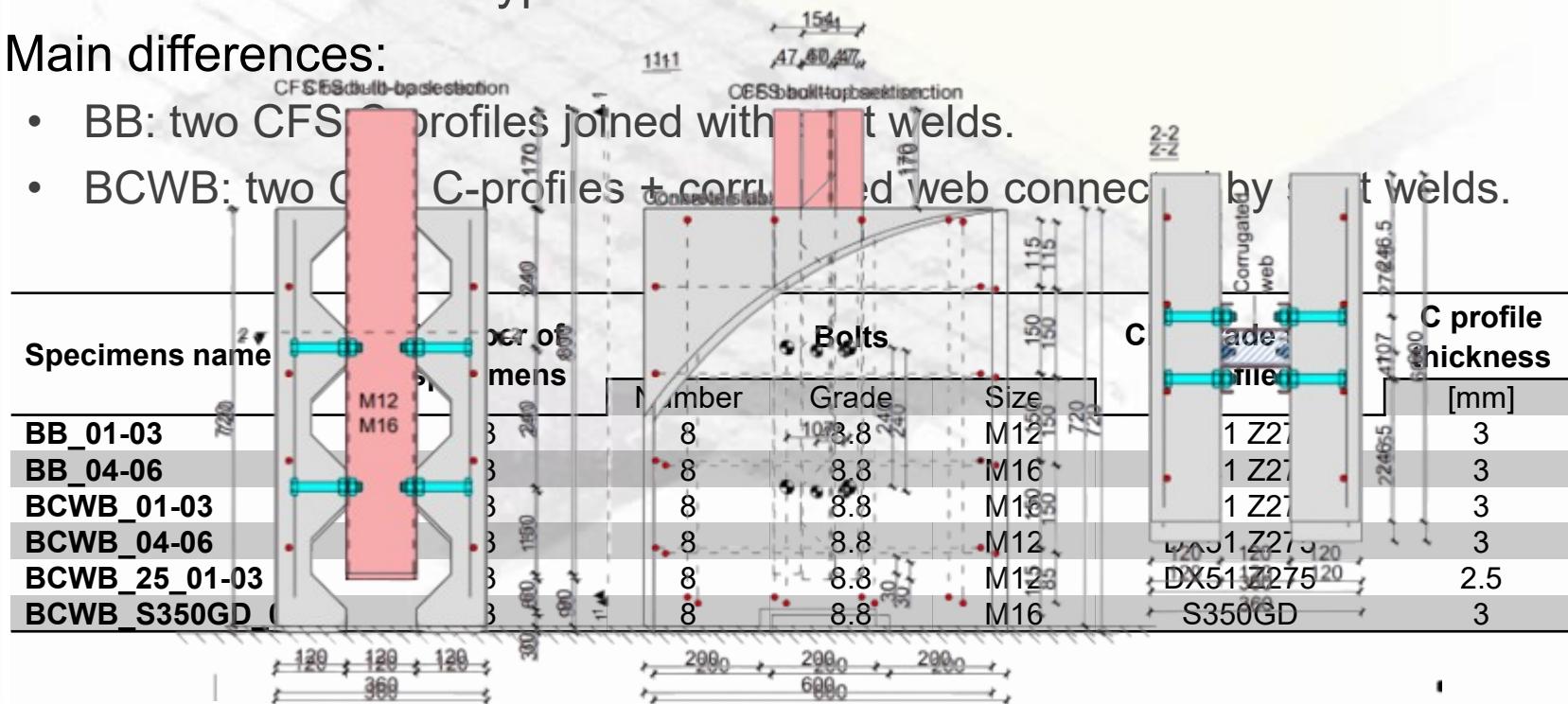
2. Literature review

- Lack of standards: No established analytical methods for CFS composite beams (existing EN 1994-1-1 mainly applies to hot-rolled steel and welded studs)
- Eurocode EN 1994-1-1 [77]: Defines shear resistance of welded studs (in solid and profiled slabs) as the minimum of steel and concrete failure.
- New prEN 1994-1-1 [78]:
 - Introduces correction factors (k_{cc} , k_t , k_l) and geometric limitations.
 - Provides calculation method for bolted connections (Annex J) with $P_{b,Rd}$ and $P_{c,Rd}$ formulas.
- CFS specificity: Bearing failure of the bolt hole often governs due to thin sections → requires calculation according to EN 1993-1-3.
- Main challenges:
 - Inaccurate predictions using existing methods for CFS bolted connections.
 - Need for reduction factors that correctly account for the geometric influence of profiled sheeting.

3. Experimental research

3. Experimental research

- Experimental research includes a total of 18 push-out tests
- Two series:
 - BB (6 specimens): Back-to-back CFS sections with demountable bolted shear connection in reinforced concrete slab with open trough sheeting.
 - BCWB (12 specimens): Built-up CFS corrugated web section with the same shear connection type.
- Main differences:
 - BB: two CFS C-profiles joined with bolted shear welds.
 - BCWB: two CFS C-profiles + corrugated web connected by bolted shear welds.

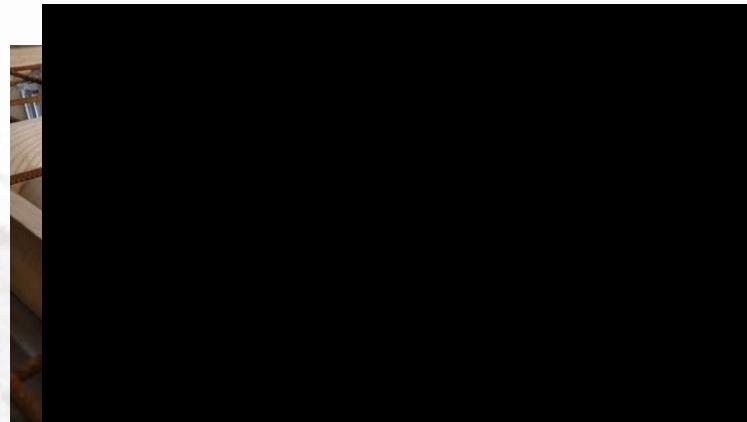


3. Experimental research

Fabrication process of the push-out specimens

Casting and preparation of concrete slabs

Phase 1



Final assembly of push-out specimens

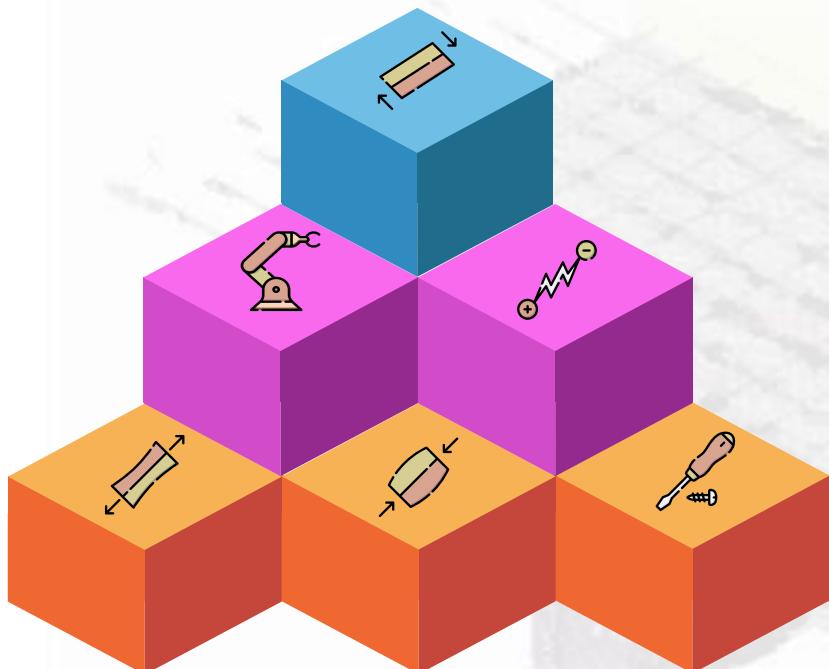
Phase 3



Phase 2
Assembly of concrete sections
spot welding



3. Experimental research



Phase 1

Base material:

- CFS sheets
- bolts
- concrete
- reinforcement



Phase 2

Investigation the resistance
of spot welds



Phase 3

Testing push-out specimens

3. Experimental research



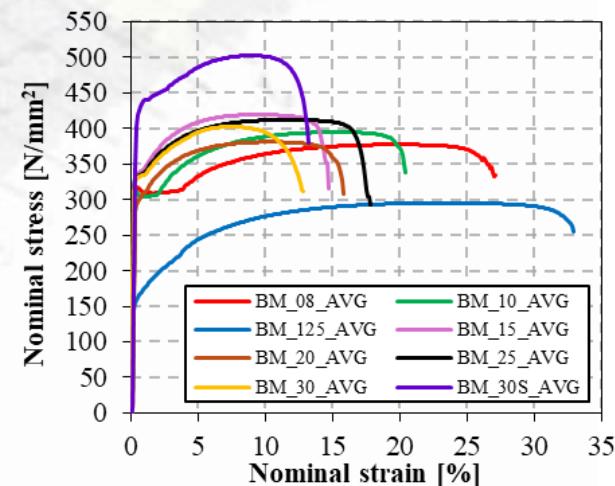
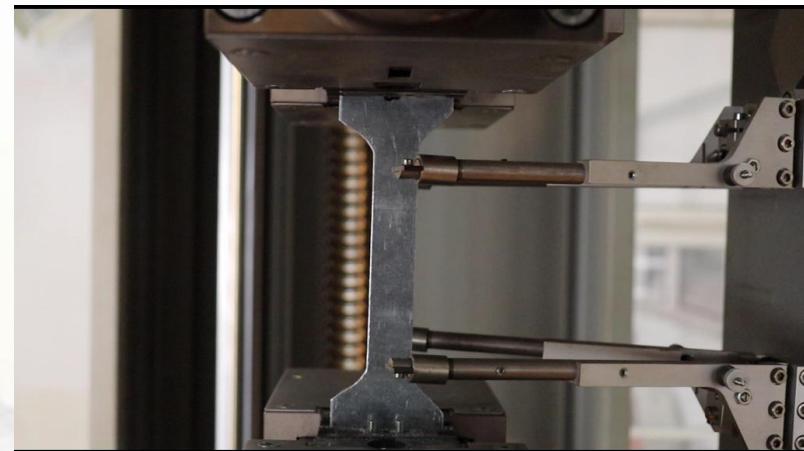
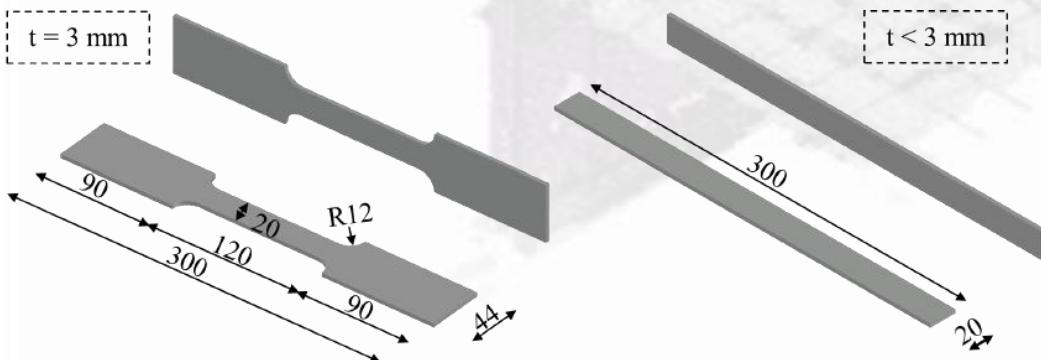
Phase 1



01. CFS sheets

Thickness of tested steel sheets:

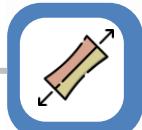
- 0.8 mm
- 1.0 mm
- 1.25 mm
- 1.5 mm
- 2.0 mm
- 2.5 mm
- 3.0 mm



3. Experimental research



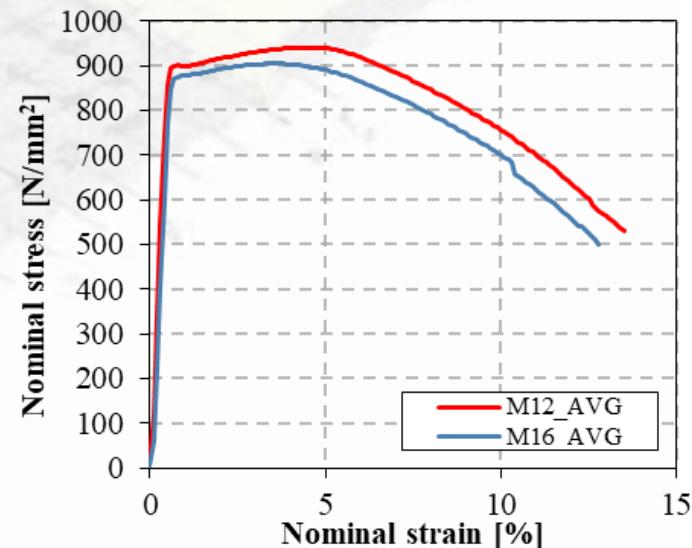
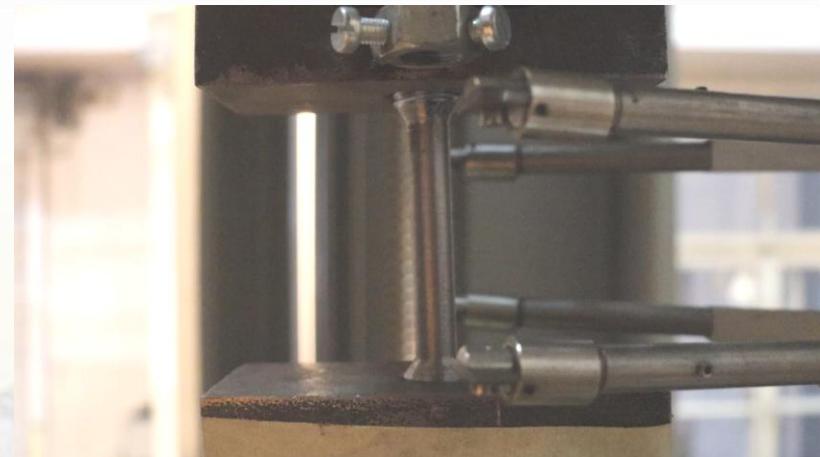
Phase 1



01. CFS sheets



02. Bolts



3. Experimental research



Phase 1



01. CFS sheets



02. Bolts



03. Concrete

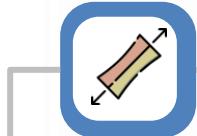


	Normal heavy concrete	Lightweight aggregate concrete		
	f_{cm} [MPa]	E_{cm} [GPa]	f_{cm} [MPa]	E_{cm} [GPa]
Mean value	28.1	29.53	18.9	17.8
St. dev. [%]	2.43	0.281	3.59	0.37
CoV[%]	8.65	0.95	19.0	2.05
Characteristic	24.5	28.8	12.6	16.9

3. Experimental research



Phase 1



01. CFS sheets



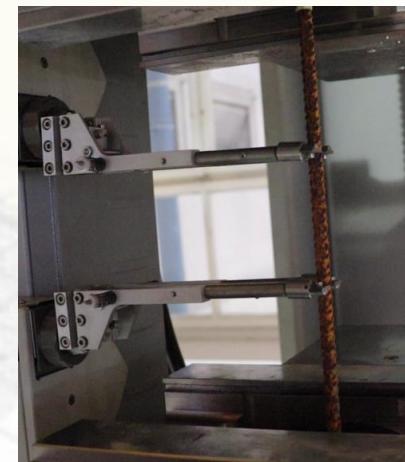
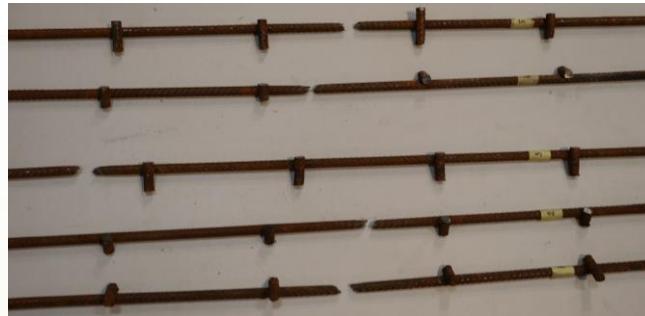
02. Bolts



03. Concrete



04. Reinforcement



	f_y [MPa]	f_u [MPa]
Mean value	513.1	598.1
St. dev. [%]	30.61	10.98
CoV[%]	5.97	1.84

3. Experimental research



Phase 2

Combination of sheet thicknesses for spot welds:

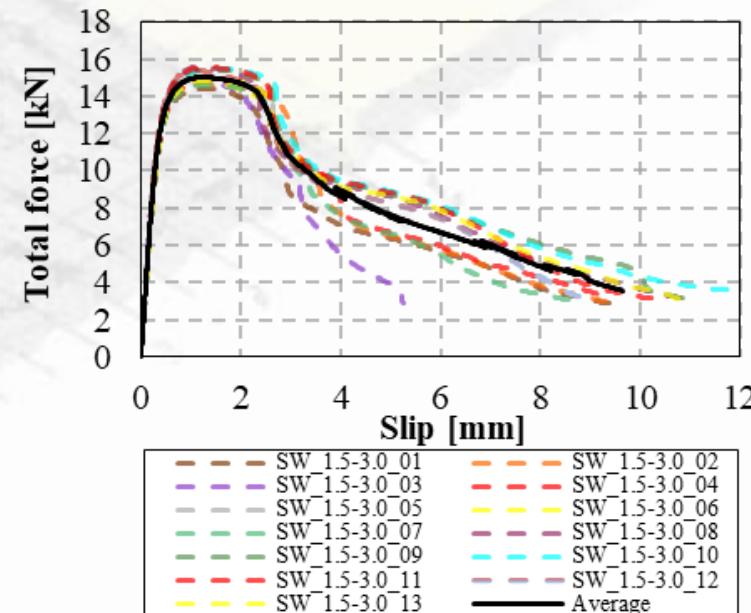
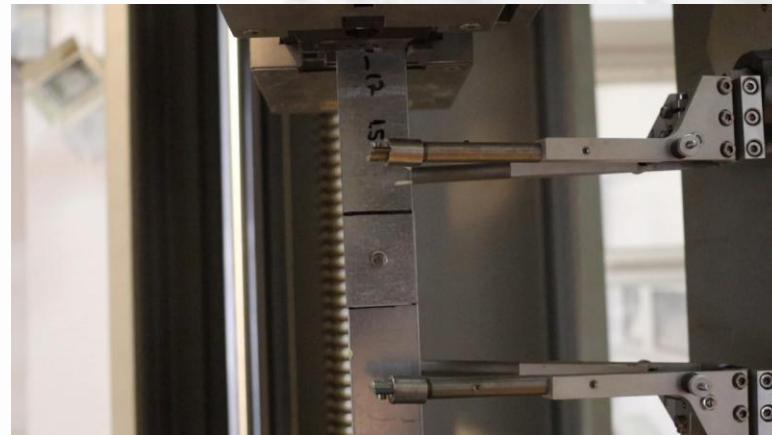
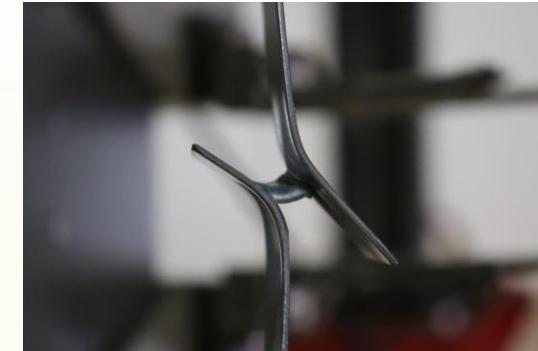
- 0.8 mm – 0.8 mm
- 0.8 mm – 1.0 mm
- 0.8 mm – 1.25 mm
- 0.8 mm – 1.5 mm
- 0.8 mm – 2.0 mm
- 0.8 mm – 2.5 mm
- 0.8 mm – 3.0 mm
- 1.0 mm – 1.0 mm
- 1.0 mm – 1.25 mm
- 1.0 mm – 1.5 mm
- 1.0 mm – 2.0 mm
- 1.0 mm – 2.5 mm
- 1.0 mm – 3.0 mm
- 1.25 mm – 1.25 mm
- 1.25 mm – 1.5 mm
- 1.25 mm – 2.0 mm
- 1.25 mm – 2.5 mm
- 1.25 mm – 3.0 mm
- 1.5 mm – 1.5 mm
- 1.5 mm – 2.0 mm
- 1.5 mm – 2.5 mm
- 1.5 mm – 3.0 mm
- 2.0 mm – 2.0 mm
- 2.0 mm – 2.5 mm
- 2.0 mm – 3.0 mm
- 2.5 mm – 2.5 mm
- 2.5 mm – 3.0 mm
- 3.0 mm – 3.0 mm

• **Total: 558 specimens**

3. Experimental research



Phase 2

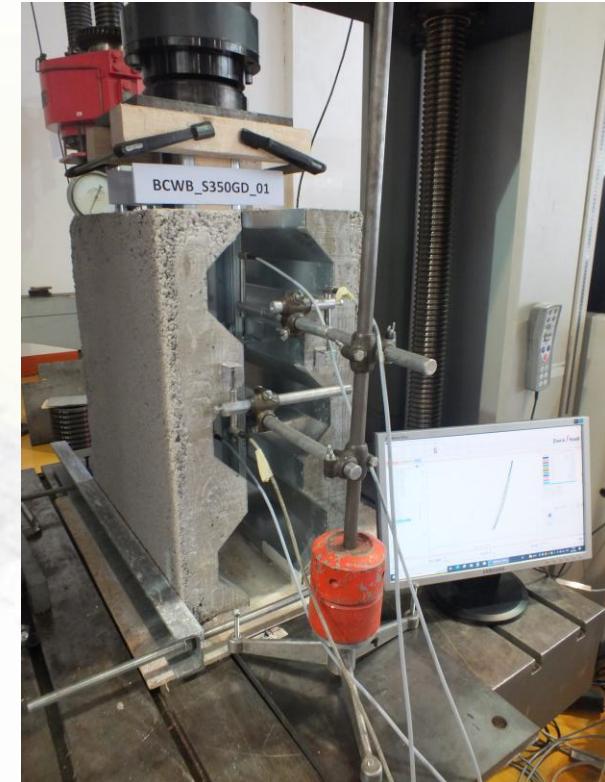


3. Experimental research



Phase 3

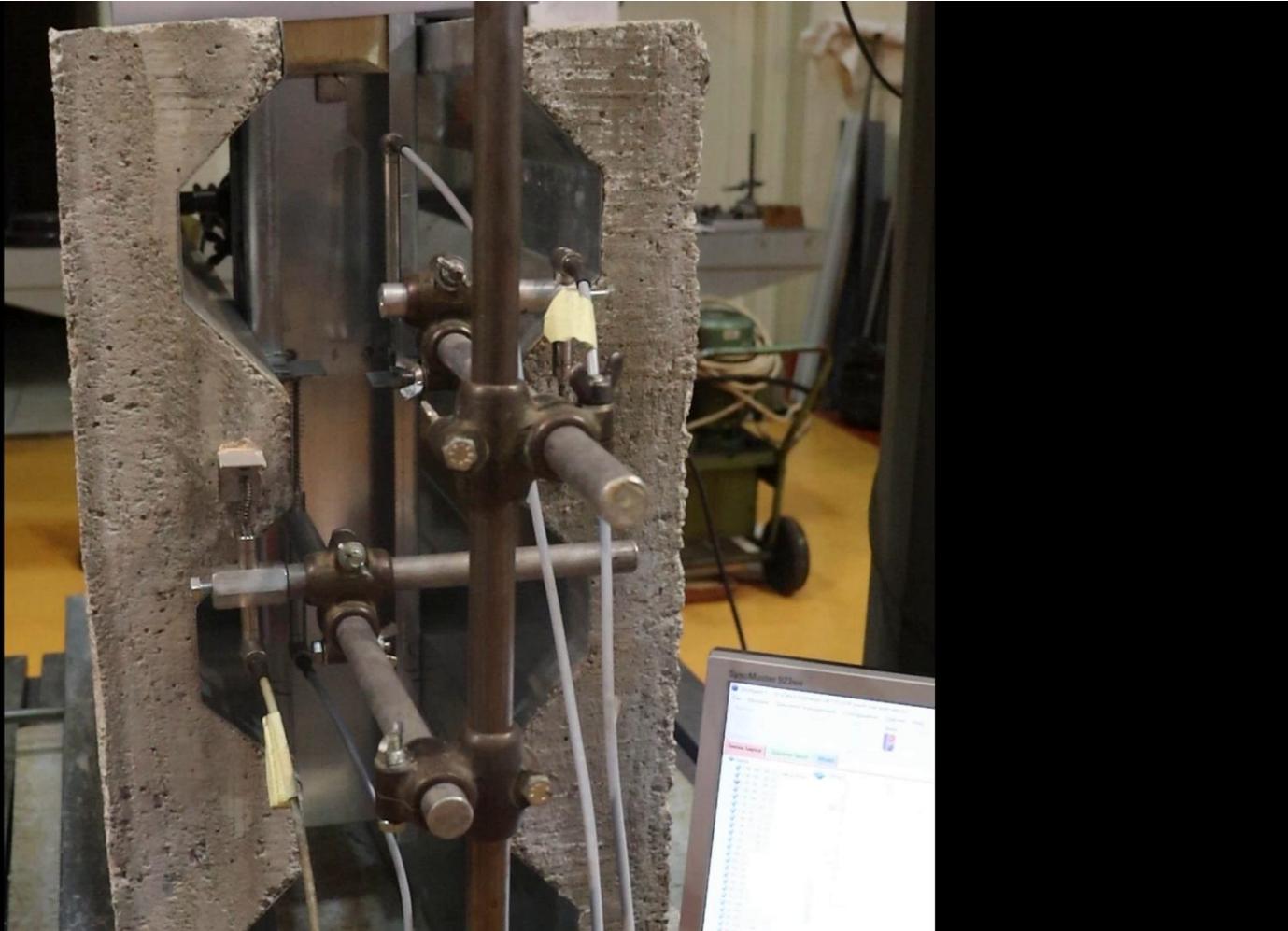
- Testing machine: static frame, EN 1994-1-1 Annex B
- Levelling: gypsum layer → reduces eccentricity, ensures contact
- Supports: steel U-profiles → prevent slab separation
- Load application: hinge → steel plate → uniform on CFS section
- Stiffening: wood brackets prevent local buckling
- 8 LVDTs:
 - 4 longitudinal displacements (V1–V4)
 - 4 slab–gypsum indentation (H1–H4)
- Load cell: 600 kN



3. Experimental research



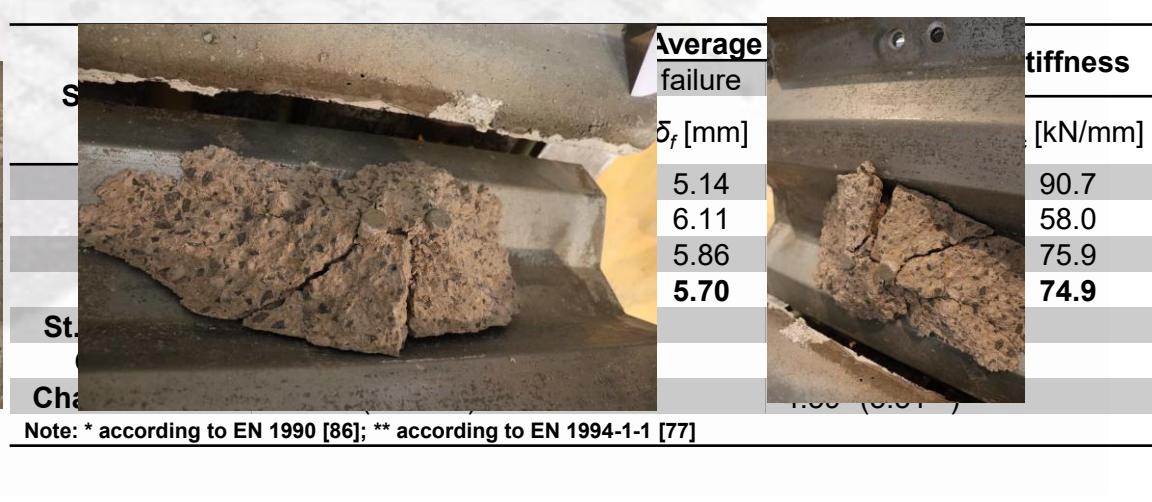
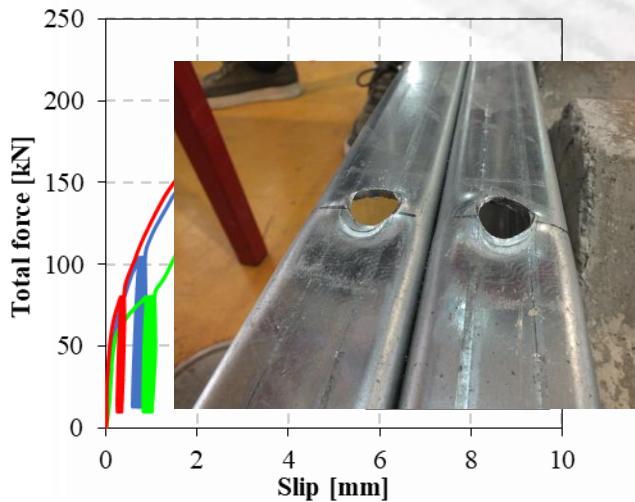
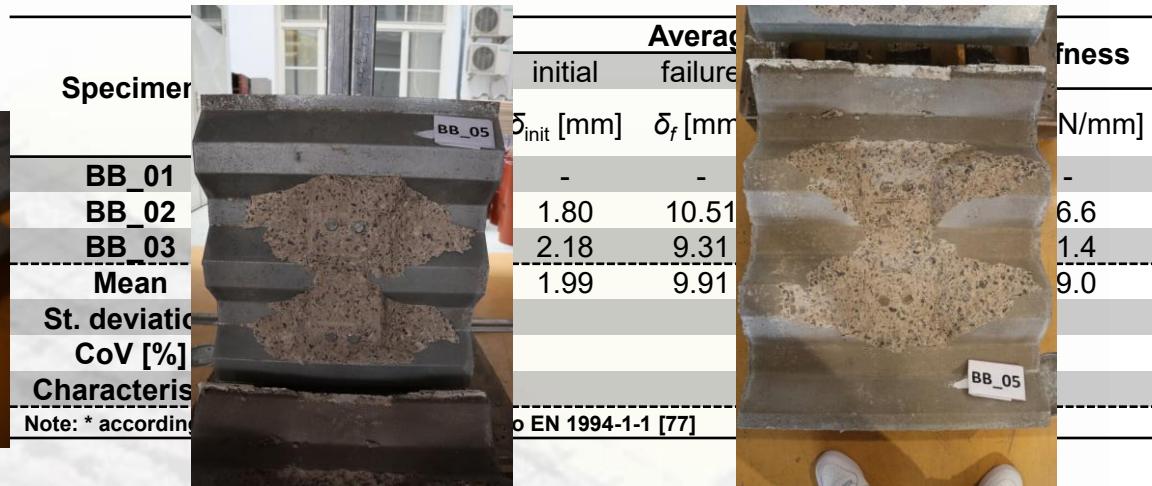
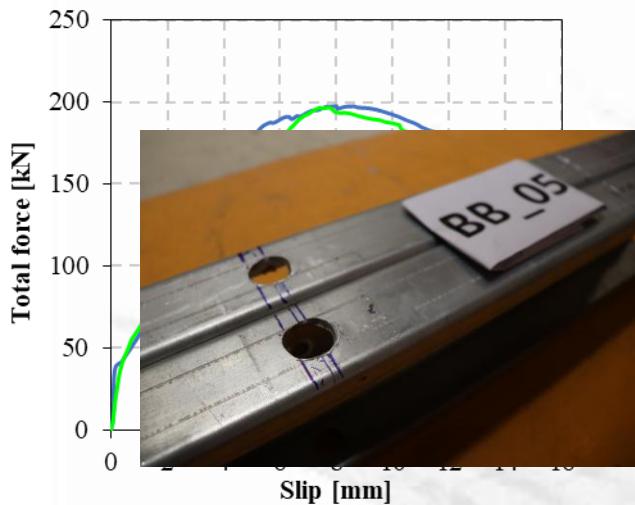
Phase 3



3. Experimental research



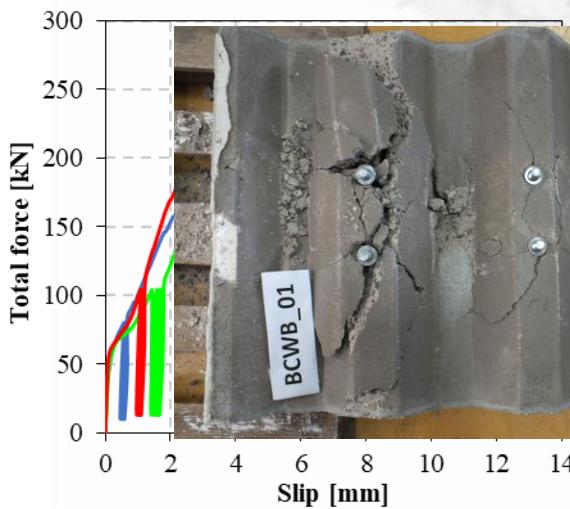
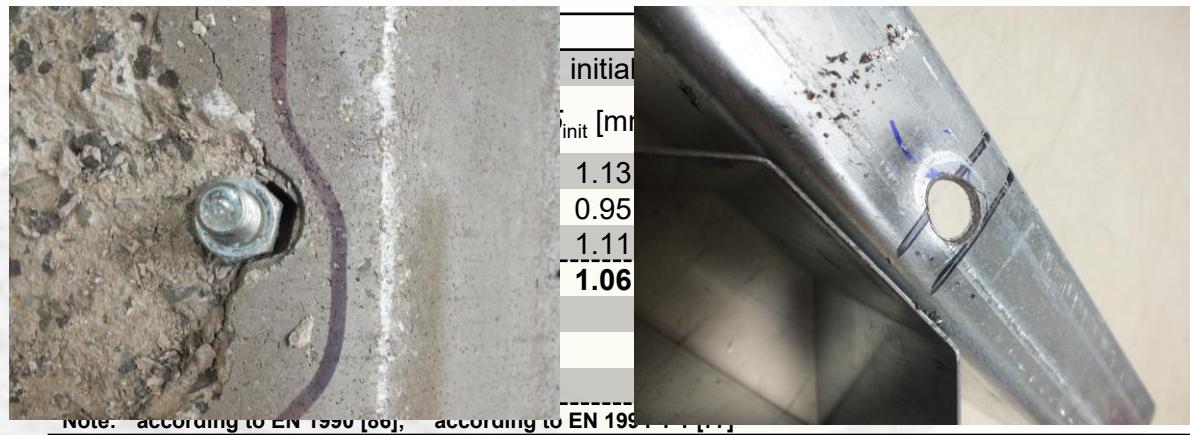
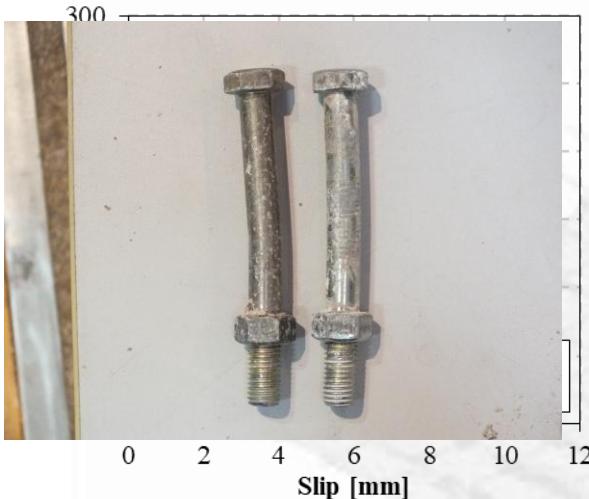
Phase 3



3. Experimental research



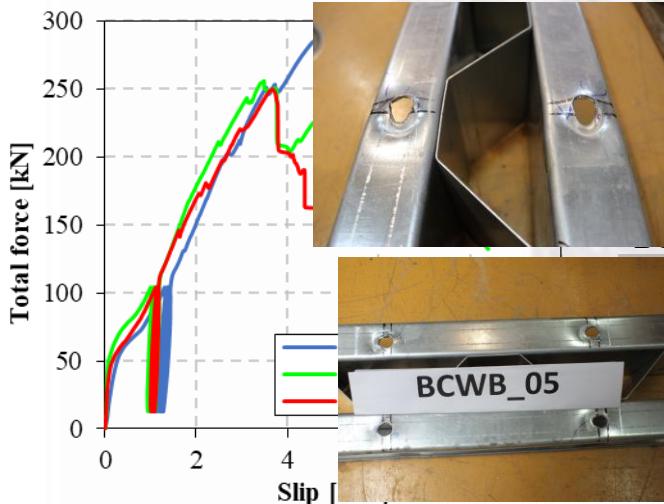
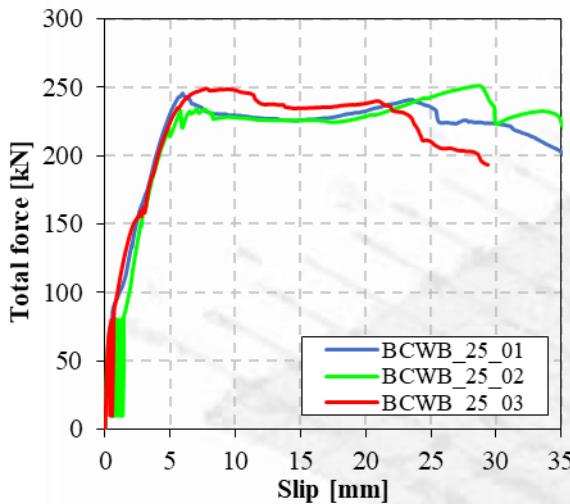
Phase 3



3. Experimental research



Phase 3



Specimen	Ultimate force		Average slip			Stiffness
	P_{ult} [kN]	δ_{init} [mm]	δ_f [mm]	δ_u [mm]	k_{sc} [kN/mm]	
BCWB_25_01	245.6	0.72	30.45	31.17	60.9	
BCWB_25_02	251.1	1.36	33.74	35.10	54.1	
BCWB_25_03	249.1	0.55	23.25	23.80	60.0	
Mean	248.6	0.88	29.15	30.02	58.3	
St. deviation	2.78			5.74		
CoV [%]	1.12			19.11		
Characteristic	239.4* (221.0**)			15.1* (21.4**)		

Note: * according to EN 1990 [86]; ** according to EN 1994-1-1 [77]

Specimen	Ultimate force		Average slip			Stiffness
	P_{ult} [kN]	δ_{init} [mm]	δ_f [mm]	δ_u [mm]	k_{sc} [kN/mm]	
BCWB_25_03	245.6	0.72	30.45	31.17	60.9	
BCWB_05	251.1	1.36	33.74	35.10	54.1	
BCWB_S_01	249.1	0.55	23.25	23.80	60.0	
Mean	248.6	0.88	29.15	30.02	58.3	
St. deviation	2.78			5.74		
CoV [%]	1.12			19.11		
Characteristic	239.4* (221.0**)			15.1* (21.4**)		

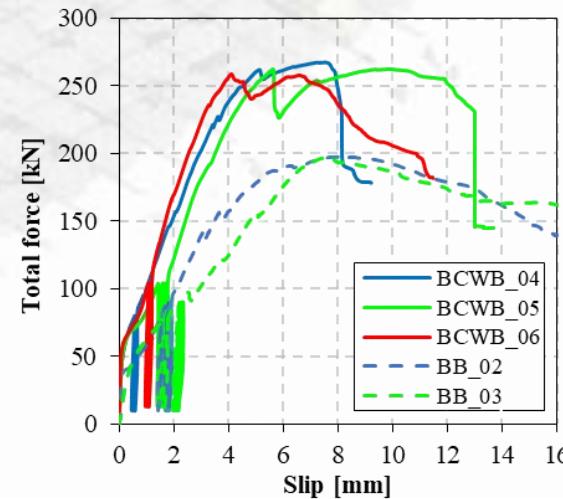
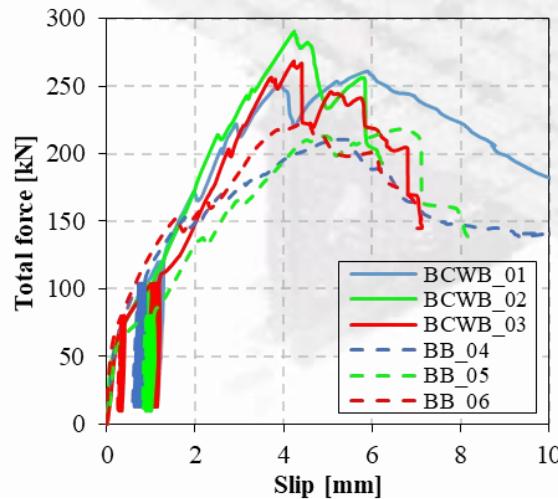
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3. Experimental research



Phase 3

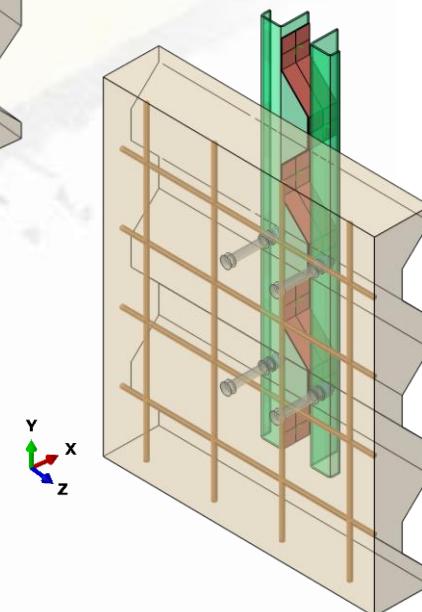
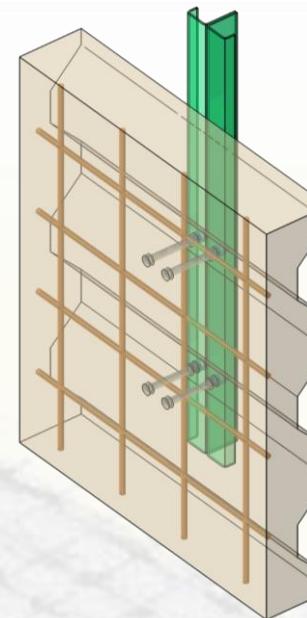
- Influence of corrugated web
 - Ultimate force: +25% with corrugated web
 - 16 mm bolts: negligible effect on ductility & stiffness
 - 12 mm bolts: ductility +20%, stiffness +80%
 - Variations due to uneven/delayed bolt–hole contact & minor specimen movement
 - Key reason: larger transverse spacing ($\approx 2.2 \times$) → better concrete bearing capacity
 - BB specimens: smaller spacing → earlier crack overlap → reduced strength



4. Finite element analysis

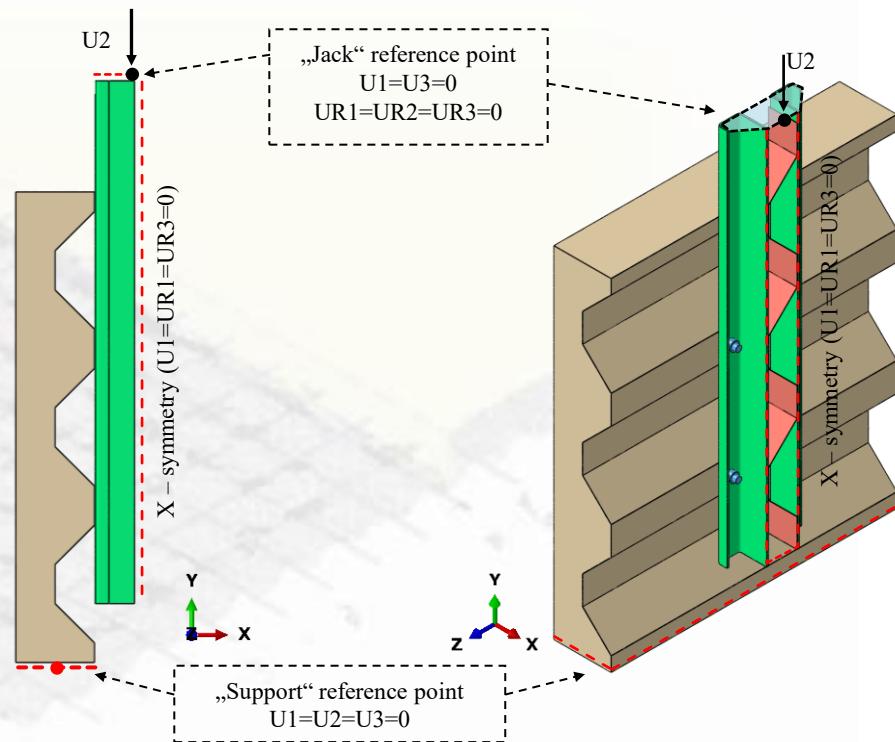
4. Finite element analysis

- Goal: Numerical study of demountable bolted shear connections in CFS–concrete systems
- Software: Abaqus, explicit solver → accounts for geometry & material nonlinearities
- Validation: FE models calibrated & compared with experimental push-out tests
- Two systems configuration:
 - Built-up CFS corrugated section
 - Back-to-back CFS section



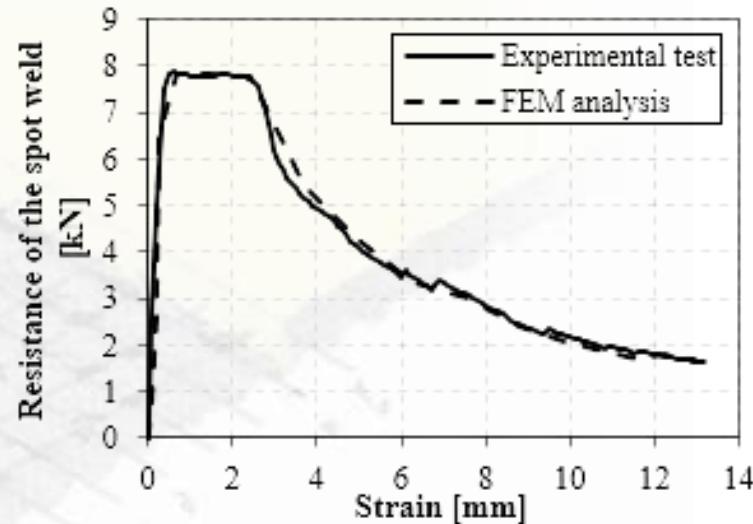
4. Finite element analysis

- Boundary Conditions
 - Symmetric boundary conditions
 - Plane orthogonal to the X-axis
 - Bottom concrete plane
 - All directions
 - CFS top
 - Horizontal directions
- Load
 - Uniform vertical displacement at the CFS top
 - Smoothed amplitude



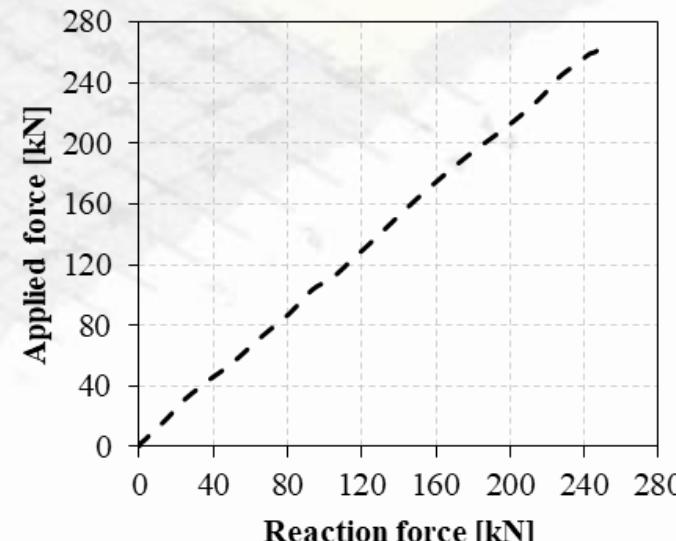
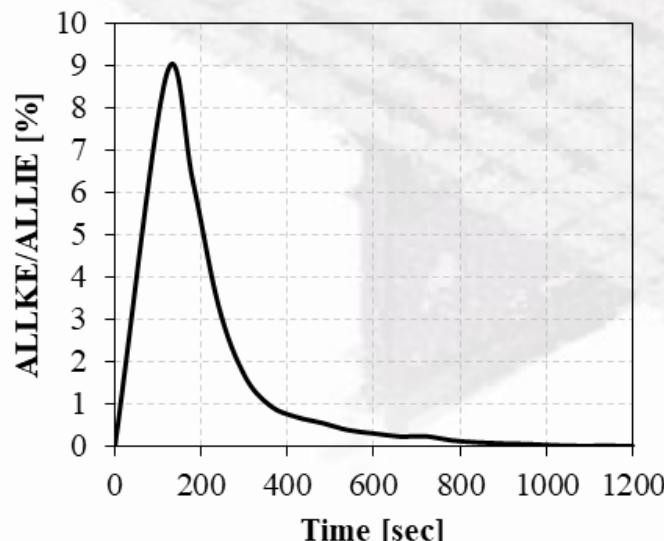
4. Finite element analysis

- Interaction
 - Normal behaviour
 - Hard contact
 - Tangential behaviour
 - Penalty friction [bolts–CFS (0.3), CFS–sheet (0.2), bolt–concrete (0.7), slab–sheet (0.1)]
 - Spot welds
 - Bushing type connectors
 - Elasticity, Plasticity, Damage and Failure characteristics



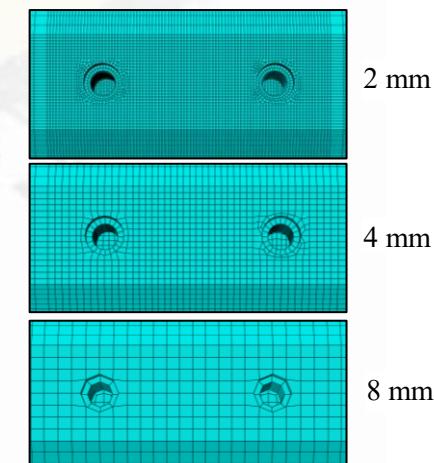
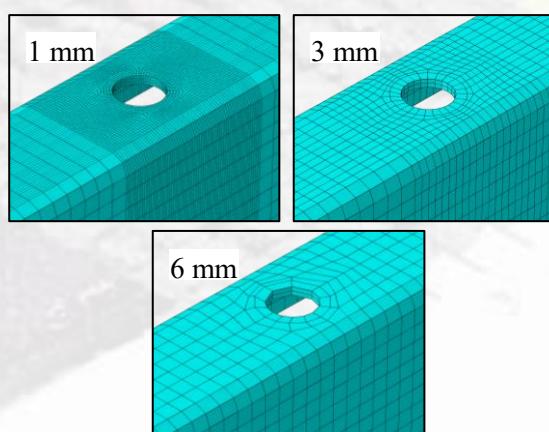
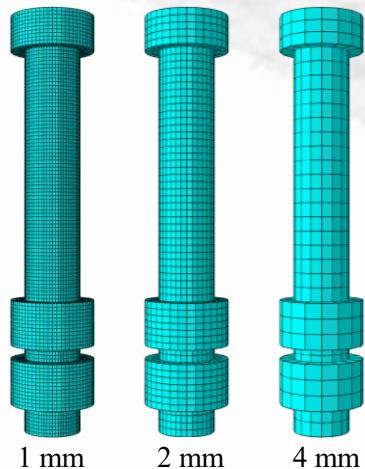
4. Finite element analysis

- Analysis method & accuracy
 - Explicit solver chosen to handle nonlinearities → quasi-static ensured by slow loading
 - Mass scaling: $\Delta t = 0.006$ s; kinetic energy <10% of internal energy
 - Force control: Input vs. output force matched → minimal inertial effects



4. Finite element analysis

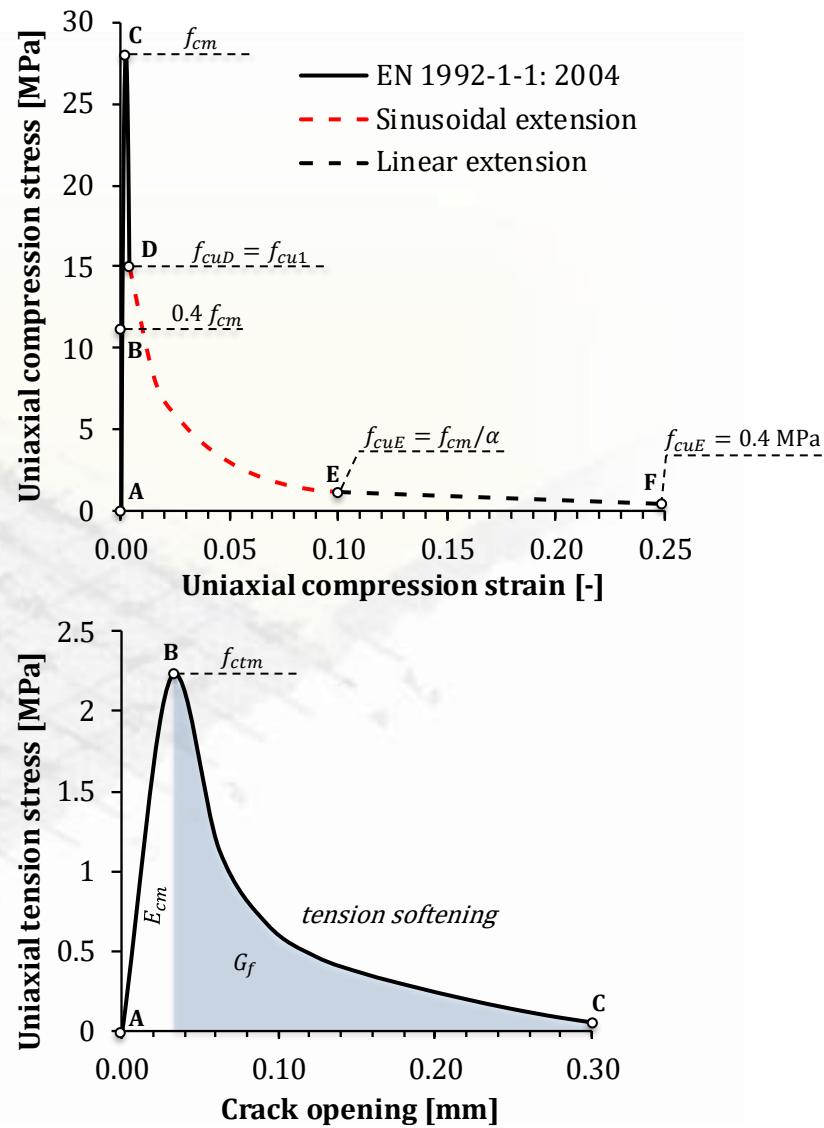
- **Mesh:**
 - Concrete, bolts, CFS
 - Profiled steel sheeting, corrugated web
- Reinforcement
 - Bolt mesh 1 mm (selected)
 - Bolt mesh 2 mm
 - Bolt mesh 4 mm
- C3D8R elements
 - CFS section mesh 1 mm (selected)
 - CFS section mesh 3 mm
 - CFS section mesh 6 mm
- T3D2 elements
- S4R elements
- Mesh sensitivity study → fine mesh around bolts & holes



8 mm

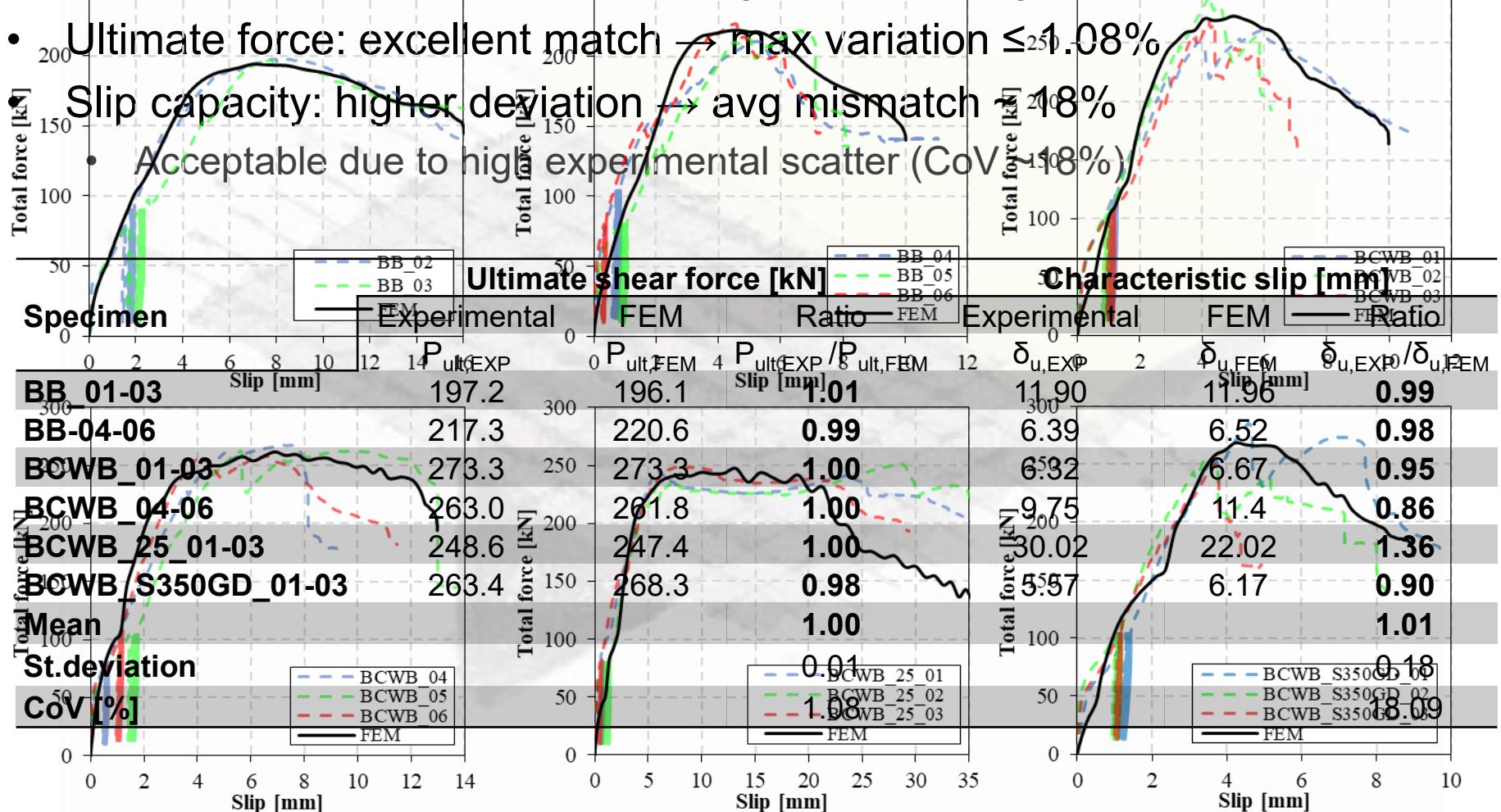
4. Finite element analysis

- Constitutive models
 - Steel
 - True stress-strain curve adopted based on experimental results
 - Concrete
 - Concrete Damage Plasticity (CDP) model
 - Captures pry-out & cracking
 - Compression failure
 - Tension failure



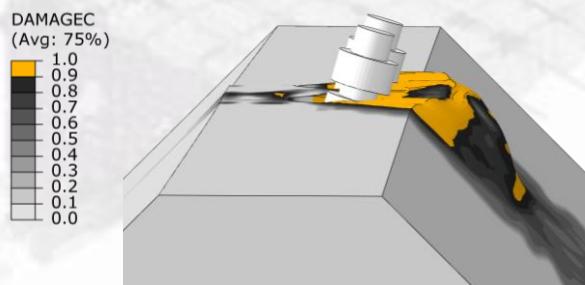
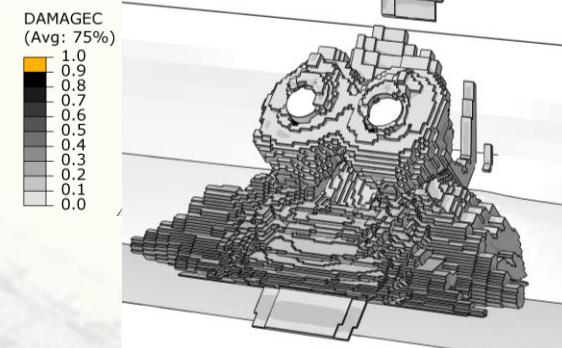
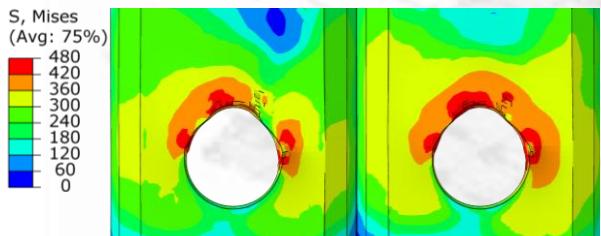
4. Finite element analysis

- Validation of FE models
- FE and experimental curves show good overall agreement



4. Finite element analysis

- Failure modes & patterns
 - FE models replicate crack formation and deformation observed in tests
 - Multiple failure modes occur simultaneously (due to thin CFS sections)
 - Resistance & ductility governed by interaction of failure mechanisms



Validated FE model selected as benchmark for parametric study

5. Numerical parametric analysis

5. Numerical parametric analysis

- Extended FE models
- Analysis across 9 variables
- Goal: establish reliable analytical procedure for resistance prediction

Parameter	Parameter label	Designation	Range
CFS section thickness	P1	t [mm]	1, 2, 2.5, 3, 4
Bolt diameter	P2	d [mm]	8, 10, 12, 14, 16, 18, 20
Embedded height of bolts	P3	h_{sc} [mm]	75-105
Concrete compressive strength	P4	f_{cm} [Mpa]	28,33,38,48
Geometry of profiled steel sheeting	P5	h_p [mm]; b_o [mm]	40-90; 120-150 ⁽¹⁾
CFS grade	P6	-	6 CFS grades ⁽²⁾
Bolt quality	P7	-	4.6, 5.6, 8.8, 10.9
Weight of concrete	P8	-	Normalweight (NC) and lightweight (LC) aggregate concrete
Type of concrete slab	P9	-	Solid (SS) and profiled (PS) slab

5. Numerical parametric analysis

- Main parametric analysis:
 - Focus on critical factors: CFS thickness, bolt diameter, concrete strength
 - Additional study of embedment height & sheeting geometry
- Additional parametric analysis:
 - Effects of CFS grade, bolt grade
 - Normal vs lightweight concrete, solid vs profiled slab configurations

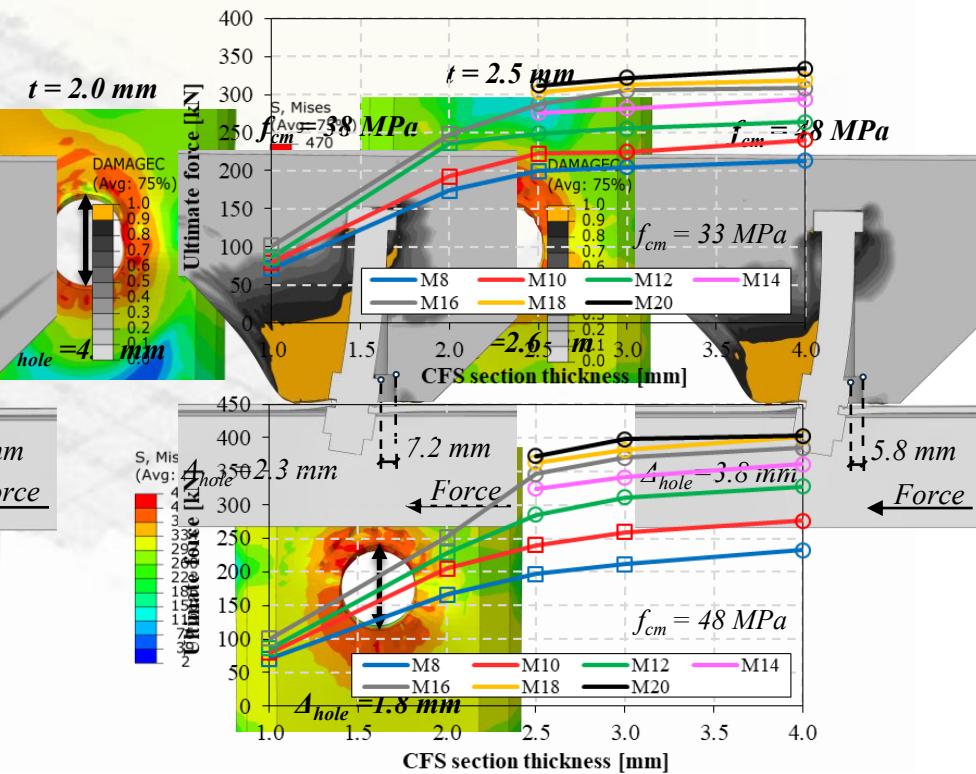
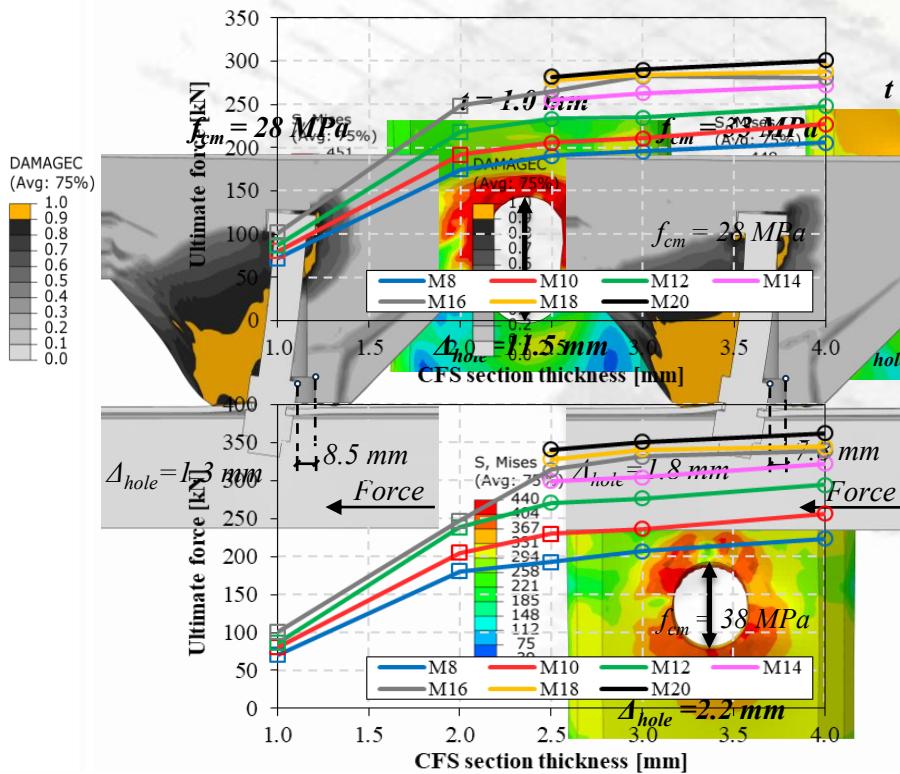
Considered values of parameters										No. of analyses
P1	P2	P3	P4	P5	P6	P7	P8	P9		
t [mm]	d [mm]	h_{sc} [mm]	f_{cm} [MPa]	h_p, b_0 [mm]	-	-	-	-		
1, 2, 2.5, 3, 4	8, 10, 12, 14, 16, 18, 20	95	28,33,38,4 8	60, 120	DX51D	8.8	NC	PS	116	Main
3	12, 14, 16,18	75-105	28,33,38,4 8	60, 120	DX51D	8.8	NC	PS	112	
3	12,16	95	28	40-90, 120-150	DX51D	8.8	NC	PS	88	
Additional	3	8, 10, 12, 16	95	28	60, 120	DX51D	4.6, 5.6, 8.8, 10.9	NC	PS	16
	3	12	95	33	60, 120	6 grades	8.8	NC	PS	6
	4	16	95	28, 33, 38	60, 120	DX51D	8.8	NC, LC	PS	6
	4	12, 14, 16	95	28	60, 120	DX51D	8.8	NC	SS,PS	6
									Σ	350

5. Numerical parametric analysis

Main analysis - Case 1 - Shear capacity

Bolt hole thickness:

- Bolt hole thickness (1.9 mm) increases shear capacity with the plasticity limit force by 70% \uparrow in f_{cm} \rightarrow only 30% \uparrow capacity with half the one coating thickness (CFS) failure
- Stronger concrete shifts failure toward CFS (bolt hole bearing)



5. Numerical parametric analysis

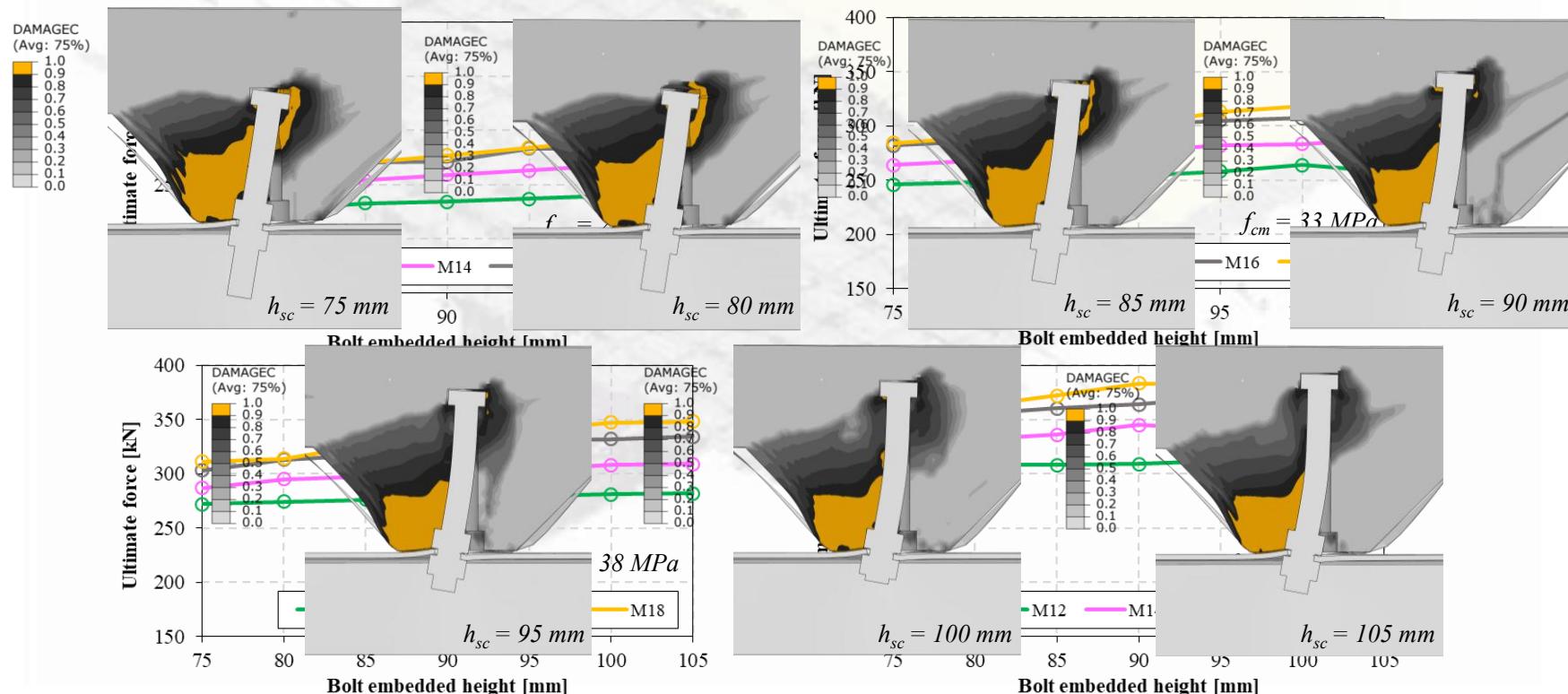
Main analysis - Case 1 - Ductility

- CFS thickness:
 - 1.0 mm → pure bolt hole bearing failure, brittle (slip < 6 mm)
 - 2.0 mm → increased slip due to interaction with concrete, ductile behaviour
 - ≥ 2.5 mm → concrete failure dominates, slip capacity decreases
- Larger bolts → stiffer, lower ductility
- Effect of concrete strength depends on bolt size
 - $d \leq 12$ mm → minimal effect
 - $d \geq 14$ mm → higher concrete strength increases slip capacity via stress redistribution
- Optimal ductility and shear capacity require balance between CFS thickness, bolt diameter, and concrete strength

5. Numerical parametric analysis

Main analysis - Case 2 - Shear capacity

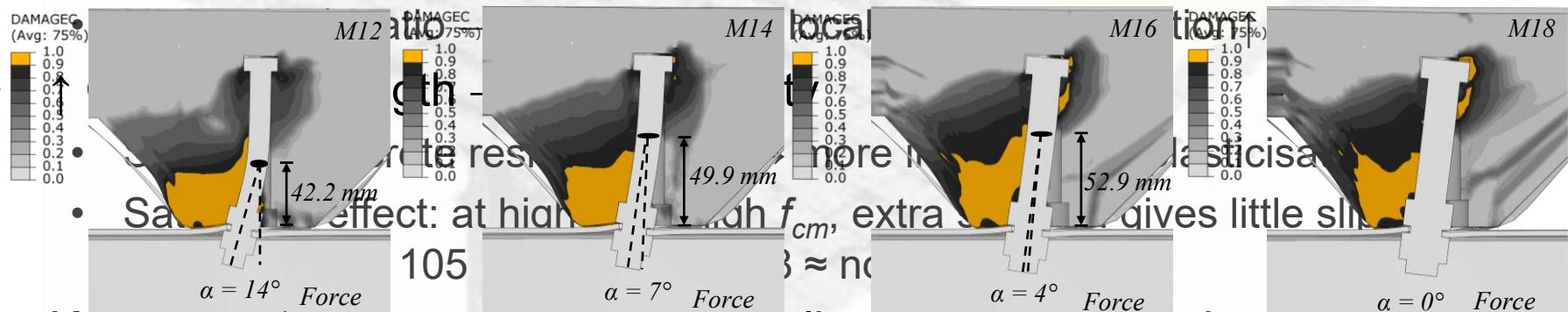
- ~~Based on bolted height height 85 mm, shear strength 112 kN, 1.2 times higher than the strength of a single bolted joint~~
- ~~Defined failure modes~~
- All models → single failure mode: concrete pry-out (half-cone cracks)
- ~~Embedment strength (hanging) depends on the concrete strength and the plastic hinge~~
→ more complex load transfer



5. Numerical parametric analysis

Main analysis - Case 2 - Ductility

- \uparrow Bolt diameter \rightarrow \downarrow slip capacity (M18 bolts = lowest slip)
 - Larger bolts = stiffer \rightarrow less bending, less interaction with concrete
 - Lower h_{sc}/d ratio \rightarrow brittle response, reduced slip capacity
- M12 bolts \rightarrow pry-out + bolt bending/plastic hinge
- M18 bolts \rightarrow pry-out only, no significant bolt deformation
- \uparrow Embedment height \rightarrow \uparrow slip capacity

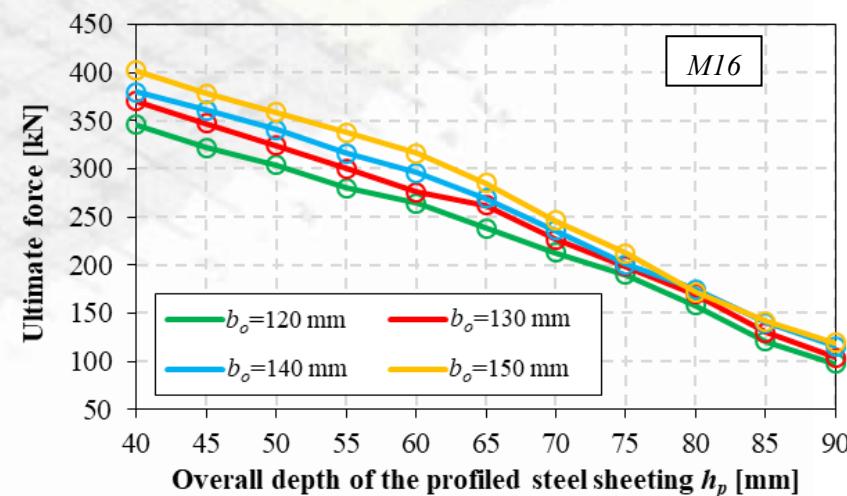
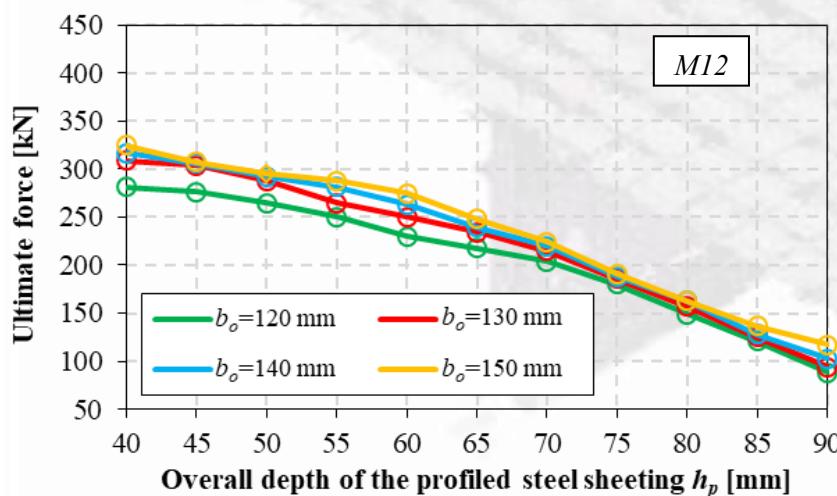


- **Key takeaway:** Large bolts reduce slip, while higher embedment height & stronger concrete improve deformation capacity → balance needed for optimal design.

5. Numerical parametric analysis

Main analysis - Case 3 - Shear capacity

- Bond diameter of profiled sheeting affects shear capacity with a wider rib (the heatless distributed situation reflected by clamping)
- Fracture models depth (a_f) by a crack tip penetration cracking concrete transition from tensile cracked at a late stage and shift failure to concrete
- Design implications width (b_f) - shear capacity must be able to be relative to slabs, thickness of the slab effect and delaying failure and avoid premature failure



5. Numerical parametric analysis

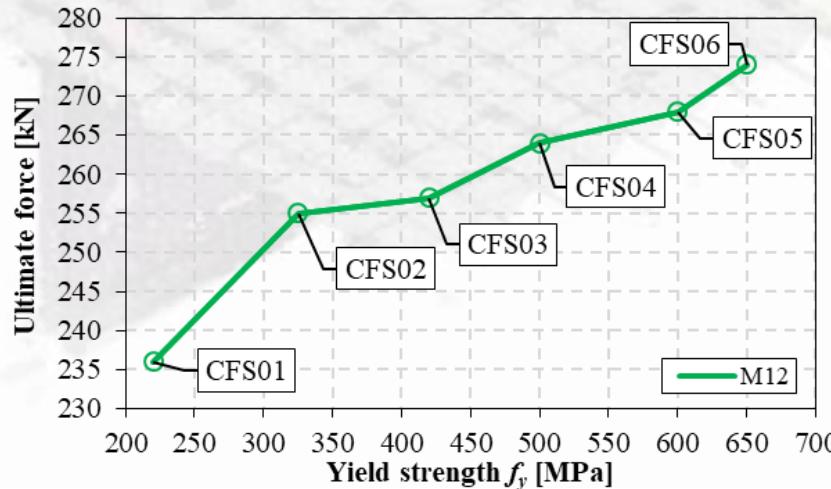
Main analysis - Case 3 - Ductility

- Increasing rib depth (h_p) → slip capacity ↓
 - At smaller h_p , stress redistributes between bolt and concrete → concrete pry-out + bolt deformation → higher ductility
 - At larger h_p , behaviour shifts → tensile cracks above ribs → more brittle response
- Increasing rib width (b_o) → slip capacity ↓ (especially at higher h_p)
 - Wider ribs → ↑ strength but ↓ ductility due to stiffer concrete confinement around the bolt
- Bolt diameter effect:
 - 12 mm bolts showed higher slip capacities at lower depths
 - 16 mm bolts improved strength but generally reduced ductility compared to 12 mm
- Design implication: Optimising rib depth and width is crucial to balance strength vs ductility in CFS-concrete bolted shear connections.

5. Numerical parametric analysis

Additional analysis - Case 1 - Shear capacity

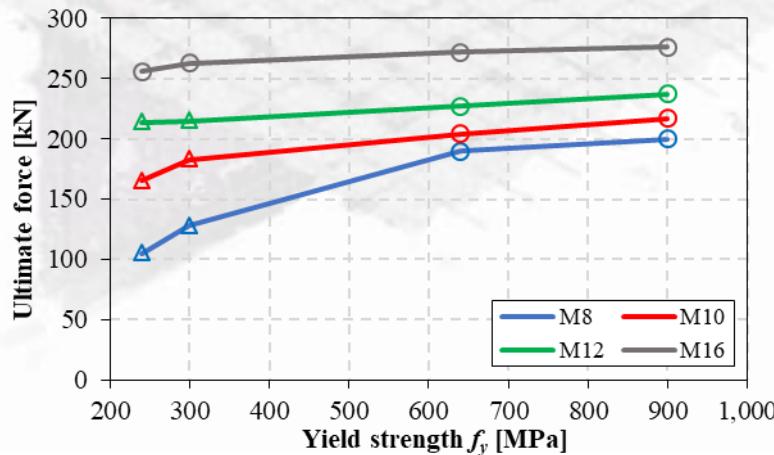
- Increasing CFS strength (CFS01 → CFS06) raised shear capacity only by ~16%, despite strength gains >200%
- Bearing failure around bolt holes is highly localized and not the governing mode in push-out models
- Concrete pry-out and bolt deformation dominate, limiting the contribution of stronger CFS sections
- Beyond a threshold, higher CFS grades give diminishing returns → not cost-efficient



5. Numerical parametric analysis

Additional analysis - Case 1 - Shear capacity

- Upgrading bolt class (4.6 → 10.9) more than doubles material strength, but shear capacity improves by only ~19%
- For small bolts (M8–M10), stronger grades directly enhance performance since bolt shear governs
- For larger bolts (M12–M16), concrete pry-out and bearing failure dominate → bolt grade has little impact
- Stronger bolts are structurally inefficient and economically unjustified when concrete governs failure.



5. Numerical parametric analysis

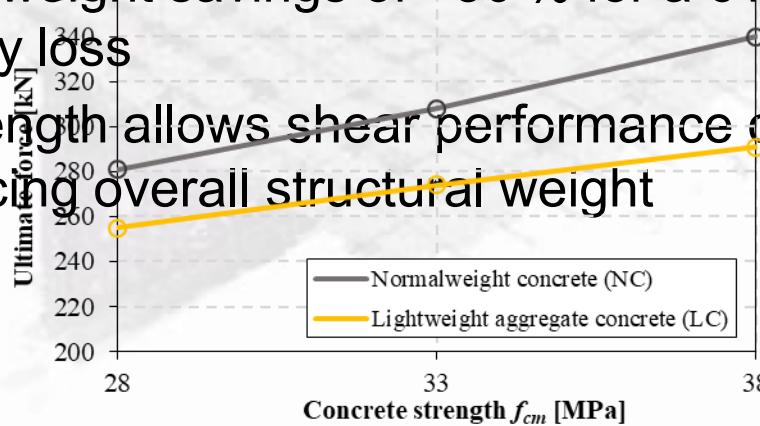
Additional analysis - Case 1 - Ductility

- CFS material properties have minimal effect on slip capacity; ductility driven by interaction of multiple failure modes
- Slip capacity strongly depends on bolt diameter and strength, with small bolts benefiting most from higher strength
- For large bolts, slip is governed by concrete pry-out; higher bolt strength may reduce ductility due to increased stiffness
- Bolt selection should consider both material and expected failure mechanisms to ensure adequate ductility

5. Numerical parametric analysis

Additional analysis - Case 2 - Shear capacity

- Normalweight concrete (NC) consistently achieves higher shear capacity than lightweight concrete (LC) across all strengths (28–38 MPa)
- Using LC results in a shear capacity reduction of 10 %–17 %, depending on concrete strength
- Failure mechanism is unchanged for both NC and LC, with concrete pry-out dominating in all cases
- LC's lower density (~30 %) makes the models significantly lighter, enabling potential weight savings of ~30 % for a 6 m composite beam with only minor capacity loss
- Optimising LC strength allows shear performance close to NC, while substantially reducing overall structural weight



5. Numerical parametric analysis

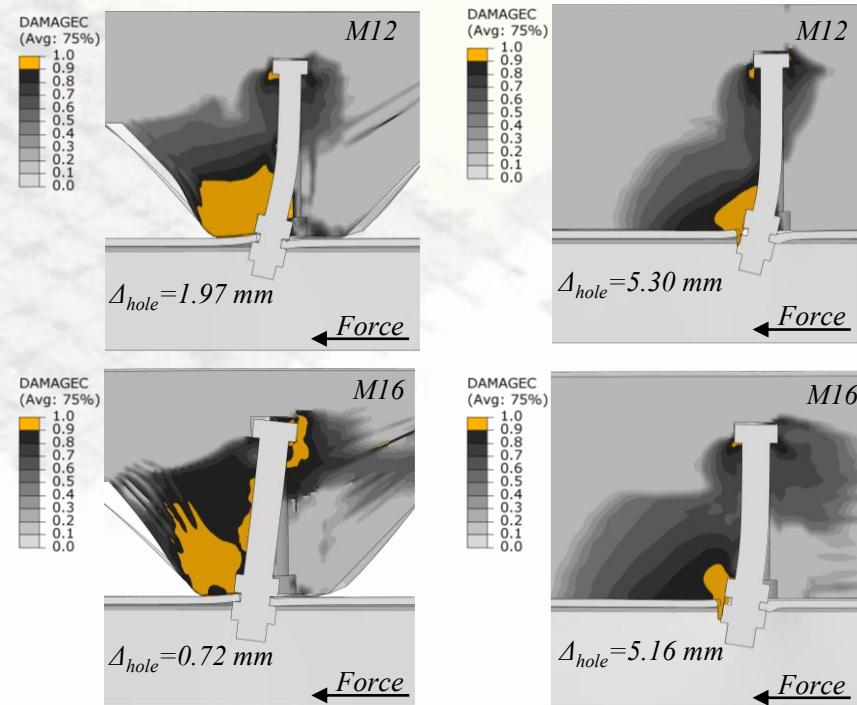
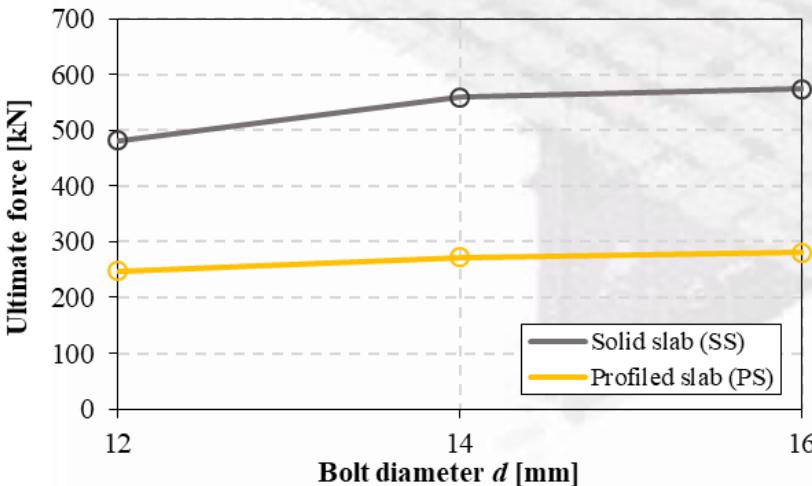
Additional analysis - Case 2 - Ductility

- Normalweight concrete (NC) consistently exhibits higher slip capacity than lightweight concrete (LC) across all strengths, indicating superior ductility
- At 28 MPa, NC slip (4.07 mm) is ~37 % higher than LC (2.98 mm)
- Reduced ductility in LC is due to strain at maximum stress equalling ultimate compressive strain, leading to earlier failure
- Optimising LC strength allows sufficient deformation capacity while benefiting from reduced structural weight.

5. Numerical parametric analysis

Additional analysis - Case 3 - Shear capacity

- SS systems show strong interaction on bolt diameter due to larger concrete volume resisting pry-out, causing stress redistribution and significant bolt and CFS deformation
- PS systems exhibit less interaction → concrete pry-out occurs without significant bolt deformation



5. Numerical parametric analysis

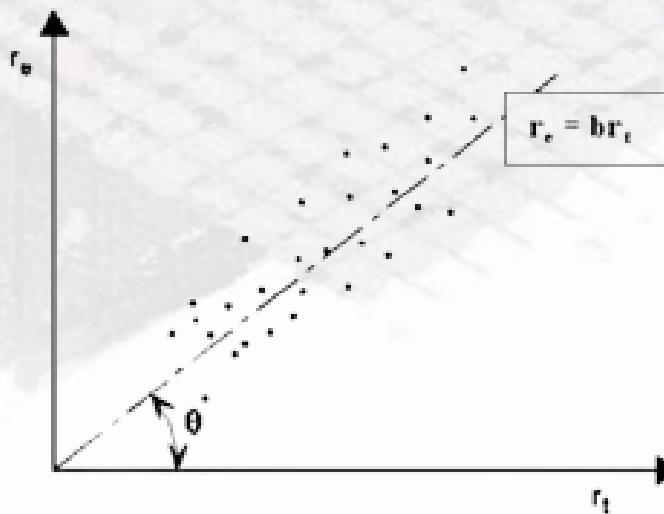
Additional analysis - Case 3 - Ductility

- Solid slabs (SS): higher slip capacity due to greater concrete volume, enabling stress redistribution across components
- Stress interaction in SS allows plastic hinge formation in the bolt, noticeable bolt bending, and elongation of the CFS bolt hole, resulting in more ductile behaviour
- Profiled slabs (PS): increasing bolt diameter reduces slip capacity, as concrete breakout occurs with minimal bolt deformation and limited interaction between failure modes
- Bolted connections in SS show higher capacity and ductility than in PS
- PS advantage: approximately 35 % weight reduction compared to SS, offering significant structural efficiency

6. Development of analytical expression for bolted shear connection resistance

6. Development of analytical expression

- Identification of two primary failure modes under shear loading:
 - Bolt hole bearing failure in the CFS section
 - Concrete pry-out failure
- Establishment of separate shear resistance criteria for each failure mode, derived from FE parametric study data
- Application of EN 1990 [86], Annex D procedure for deriving design resistance, including statistical evaluation of theoretical resistance functions.

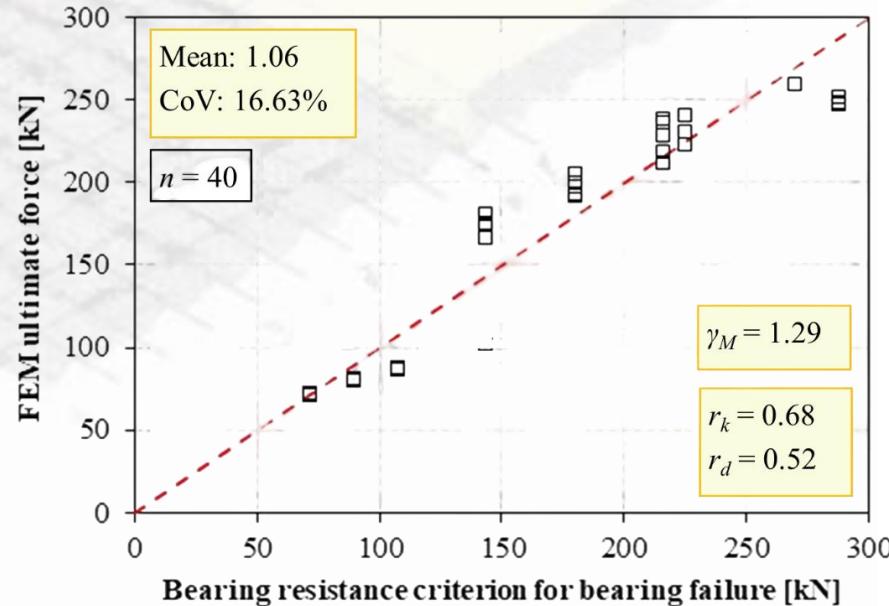


6. Development of analytical expression

Bearing failure of the bolt hole in the CFS section

- Bearing failure from FEM vs. correlation:
 - Gotcha in the CFS standard EN 1993-1-3 for small flange load in CFS sections (clear bearing failure)
- Current standard EN 1993-1-3 [81]
 - Poorer predictions when interaction of deformation modes (bolt bending, concrete pry-out, hole elongation) becomes significant
 - FEM results show frequent overestimation with high scatter ($COV \approx 16\%$)
 - Obtained $\gamma_M = 1.29 > 1.25$ target \rightarrow current criterion is unreliable.

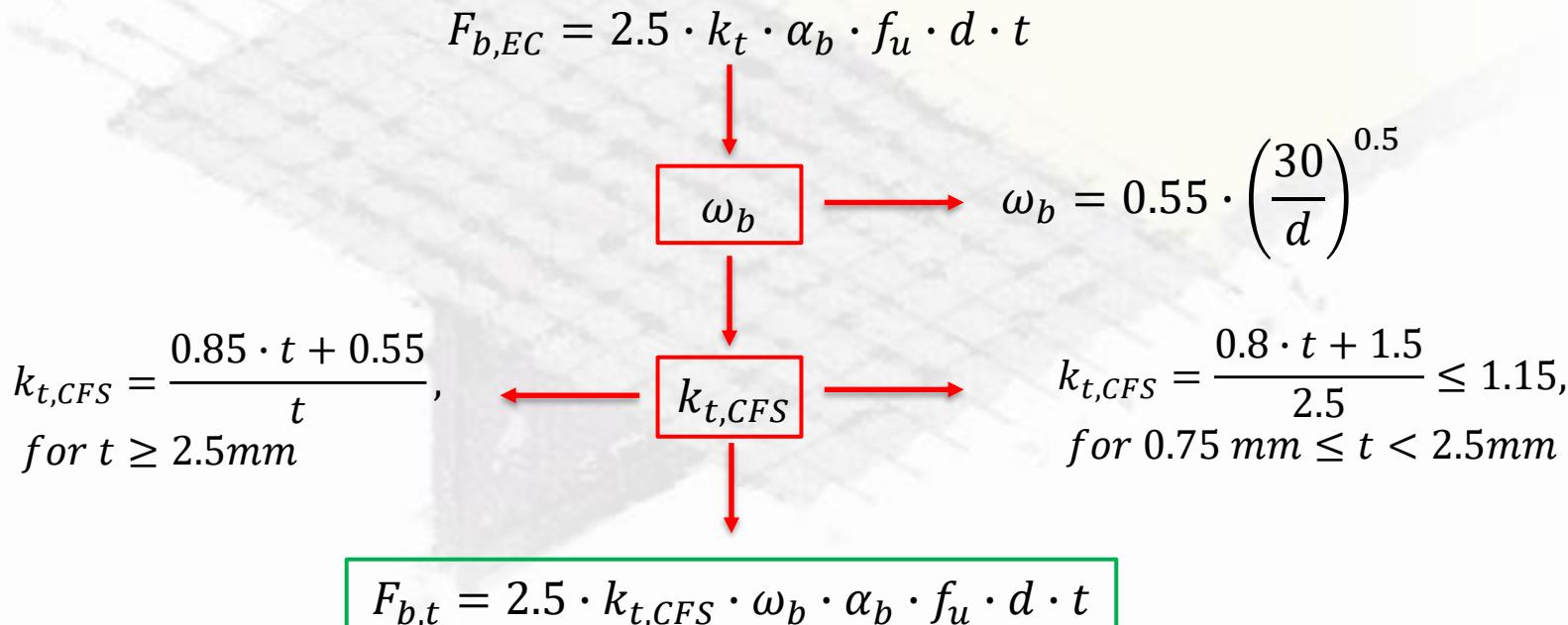
$$F_{b,EC} = 2.5 \cdot k_t \cdot \alpha_b \cdot f_u \cdot d \cdot t$$



6. Development of analytical expression

Bearing failure of the bolt hole in the CFS section

- Proposed improved criterion (Eq. 6.19):
 - Adds factor ω_b (accounts for bolt diameter influence)
 - Modifies $k_{t,CFS}$ to represent thickness effect more accurately
 - Provides better reflection of complex bolt–CFS–concrete interactions



Proposed criterion

6. Development of analytical expression

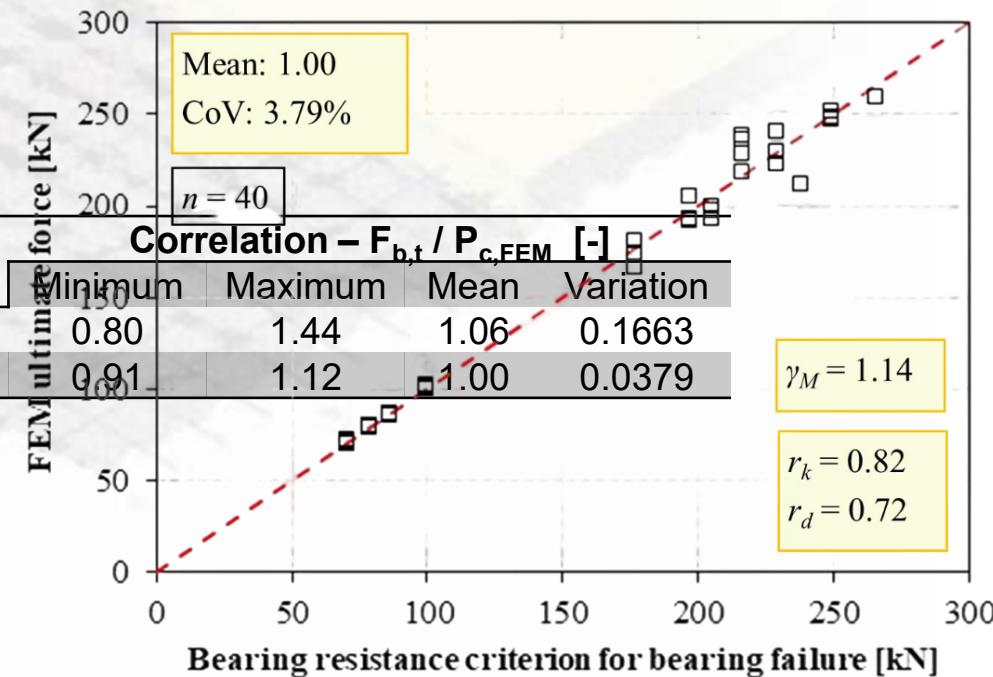
Bearing failure of the bolt hole in the CFS section

- Validation results
 - Correlation factor with FEM: 0.91–1.12, mean ≈ 1.00 , COV ≈ 0.038 (vs. 0.166 for EN 1993-1-3)
 - Partial safety factor $\gamma_M = 1.14$ (< 1.25 target) \rightarrow reliable and conservative
 - Strong statistical agreement (high r_k and r_d)

$$F_{b,t} = 2.5 \cdot \frac{\text{Bearing failure criterion}}{\rho_{t,CFS} \cdot \sigma_b \cdot f_u} \cdot t$$

EN 1993-1-3 [Eq. (6.18)]

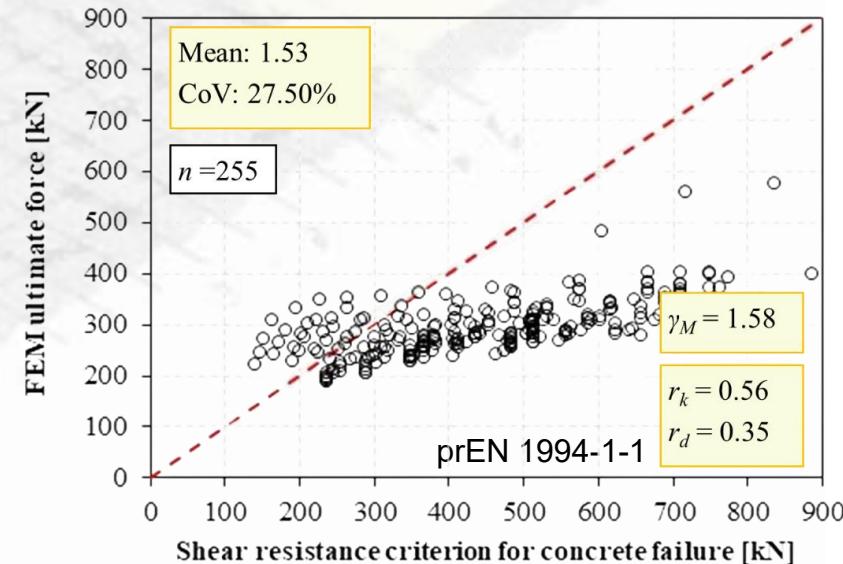
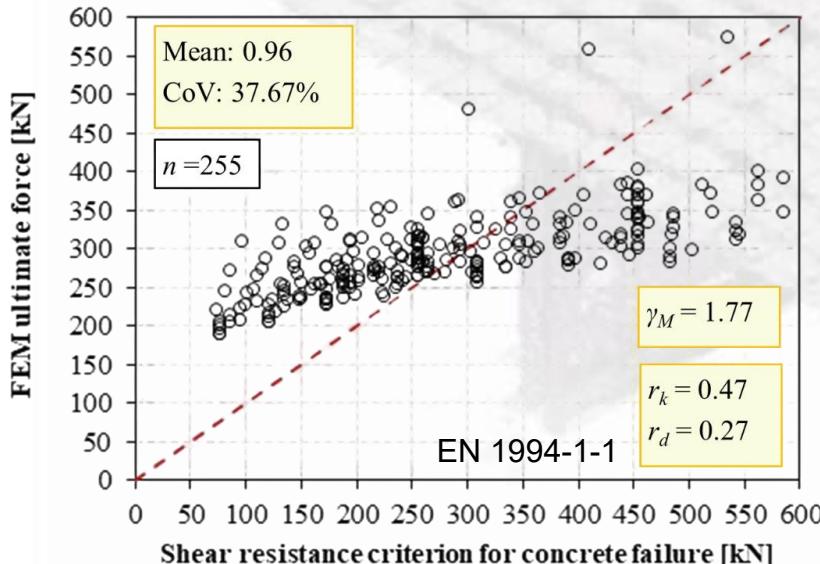
Finally proposed [Eq. (6.19)]



6. Development of analytical expression

Concrete failure

- Dominant failure mode:
 - Concrete pry-out as the critical failure mode in bolted CFS–concrete composite beams
- Existing criteria evaluated:
 - EN 1994-1-1 [77] (studs): partly conservative, but inconsistent → unreliable
 - prEN 1994-1-1 [78] (bolts): mostly overestimates resistance → still unreliable
 - Neither accounts effects of CFS thickness or multi-mode interaction

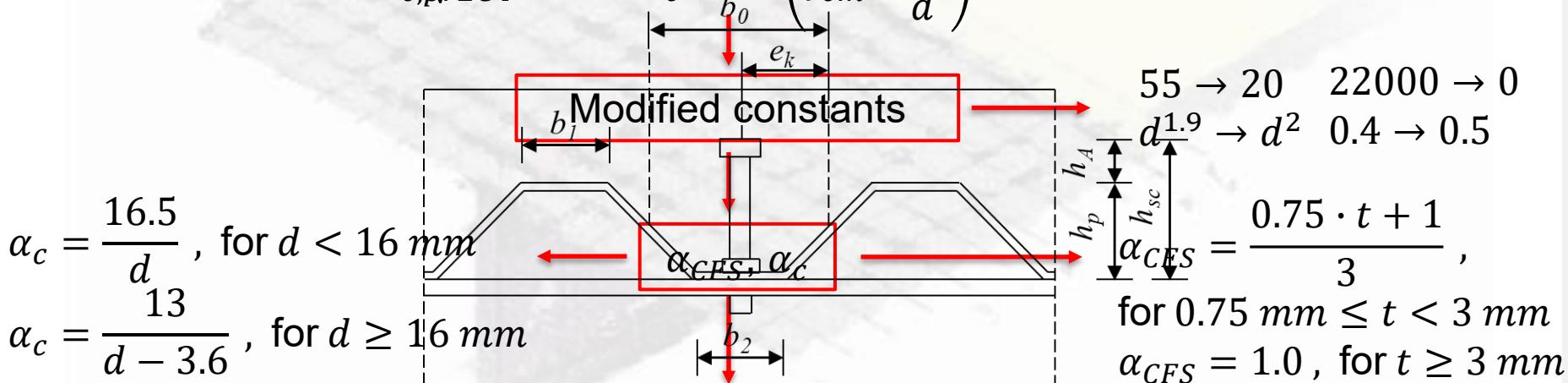


6. Development of analytical expression

Concrete failure

- Proposed criterion (Eq. 6.26):
 - Modified from prEN expression
 - Introduces α_c (bolt geometry influence) and α_{CFS} (CFS thickness effect)
 - Reduction factor k_t formulated for profiled slabs

$$k_t = \frac{1.17}{P_{c,p} \sqrt{n} E c_4} = 55 \cdot \alpha_c \cdot d^{1.9} \left(\frac{0.0008 h_{sc} b_1}{f_{cm} \cdot \frac{b_0}{d}} \right)^{0.4} + 22000 \cdot h_p$$



$$P_{c,t} = 20 \cdot \alpha_{CFS} \cdot \alpha_c \cdot d^2 \left(f_{cm} \cdot \frac{h_{sc}}{d} \right)^{0.5}$$

Proposed criterion

6. Development of analytical expression

Concrete failure

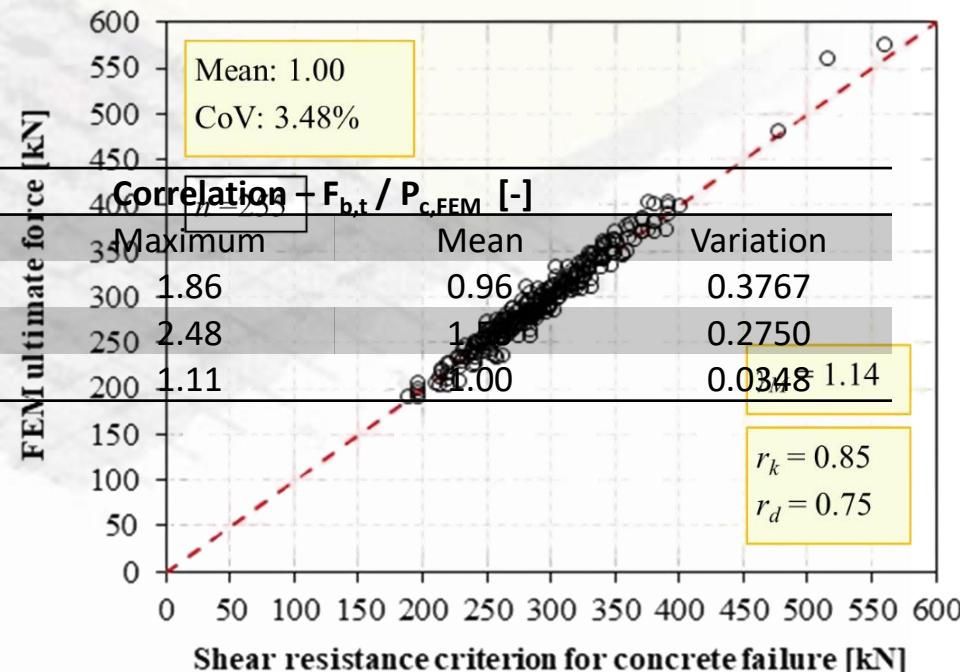
- Validation:
 - Strong correlation with FEM (mean ≈ 1.0 , COV $\approx 3.5\%$)
 - Partial safety factor $\gamma_M = 1.14 < 1.25$ target \rightarrow reliable and conservative
 - Good statistical indicators (r_k , r_d) confirm suitability

$$P_{c,t} = \frac{20 \cdot \alpha_{c,FS} \cdot \alpha_{c,Min} \cdot d^2}{\text{Concrete failure criterion}} \left(f_{cm} \cdot \frac{h_{sc}}{d} \right)^{0.5}$$

EN 1994-1-4 [Eq. (6.20)] 0.31

~~prEN 1994-1-4 [Eq. (6.22)]~~ 0.008 · $b_1 - 0.0053 h_p$

FFinally proposed [Eq. (6.26)] 0.91



6. Development of analytical expression

Design recommendations

- The application of the proposed design shear resistance:
 - Bolt geometry: Single embedded nuts → bolt diameter 12–20 mm
 - CFS section: Thickness $t \geq 2.5$ mm → ultimate tensile strength $f_u \geq 400$ N/mm²
 - Concrete: $f_{ck} \rightarrow 20 - 40$ MPa
 - Profiled sheeting: Depth $h_p \leq 0.55h_{\text{slab}}$; thickness $t_p \geq 0.70$ mm
 - Embedment: Depth $h_A \geq 0.8d$; reinforcement layer beneath bolt heads required
 - Spacing: Longitudinal $s > 5d$; transverse $s > 50$ mm
 - Applicability: Only for ribs with two bolted shear connectors

7. Reliability assessment of proposed analytical models for shear connection resistance

7. Reliability assessment of analytical models

- Need for probabilistic approach:
 - Deterministic methods neglect inherent variability in material properties and geometry
 - Variability significantly affects reliability → probabilistic analysis provides more realistic assessment
- Theoretical concept:
 - Resistance (R) and load effect (E) treated as random variables
 - Reliability defined by safety margin: $Z = R - E$
 - Failure domain: $g(X) \leq 0$, where X is the vector of basic random variables
- Methods for reliability analysis:
 - FORM (First Order Reliability Method) used here
 - Simplifies integration domain using hyper-plane approximation
 - Failure probability expressed as: $P_f = \Phi(-\beta)$, where β = reliability index.

7. Reliability assessment of analytical models

- Reliability index (β):

- Quantifies failure probability of shear connection
- Relation to mean (μ) and standard deviation (σ) of resistance and load:

$$\beta = \frac{\mu_R - \mu_E}{\sqrt{\sigma_R^2 + \sigma_E^2}}$$

- Higher $\beta \rightarrow$ lower failure probability
- Target reliability levels (EN 1990):
 - Depends on consequence class (CC) and reliability class (RC)
 - For RC2 / CC2, acceptable $\beta = 3.8$ over 50-year service life ($P_f \approx 1 \cdot 10^{-4}$)
- Application in thesis:
 - Limit state equations formulated for identified failure modes:
 - Concrete pry-out failure
 - Bearing failure of bolt hole in CFS section
 - Reliability index β computed using STRUREL software

7. Reliability assessment of analytical models

Concrete failure – Limit state equations

- General form of the limit state equations:

$$g_1(\bar{X}) = \Theta_R \cdot P_{c,R} - \Theta_E \cdot P_E = 0$$

- Substituting the resistance expressions :

$$g_1(\bar{X}) = \Theta_R \cdot k_t \cdot 20 \cdot \alpha_{CFS} \cdot \alpha_c \cdot d^2 \left(f_{ck} \cdot \frac{h_{sc}}{d} \right)^{0.5} - \Theta_E \cdot P_E = 0$$

- Variations of the limit state function → depend on CFS thickness (t) and bolt diameter (d):

$$g_{1-1}(\bar{X}) = \Theta_R \cdot 20 \cdot (0.83 + 0.0007 \cdot b_0 - 0.00008 \cdot b_1 - 0.0006 \cdot h_{pp}) \cdot \frac{13}{d - 3.6} \\ \cdot \frac{0.75 \cdot t + h_{sc}}{d^2 \left(f_{ck} \cdot \frac{h_{sc}}{d} \right)^{0.5}} - \Theta_E \cdot (P_{E,G} + P_{E,Q}) \leftarrow t \leq 3 \text{ mm, } d \leq 16 \text{ mm} \\ = 0$$

$$g_{1-2}(\bar{X}) = \Theta_R \cdot 20 \cdot (0.83 + 0.0007 \cdot b_0 - 0.0008 \cdot b_1 - 0.006 \cdot h_{pp}) \cdot \frac{16.5}{d} \leftarrow t \geq 3 \text{ mm, } d \geq 16 \text{ mm} \\ \cdot \frac{0.75 \cdot t + h_{sc}}{d^2 \left(f_{ck} \cdot \frac{h_{sc}}{d} \right)^{0.5}} - \Theta_E \left(f_{ck} \cdot \frac{h_{sc}}{d} \right)^{0.5} - \Theta_E \cdot (P_{E,G} + P_{E,Q}) = 0$$

7. Reliability assessment of analytical models

Bearing failure – Limit state equations

- General form of the limit state equations:

$$g_2(\bar{X}) = \Theta_R \cdot F_{b,R} - \Theta_E \cdot P_E = 0$$

- Substituting the resistance expressions :

$$g_2(\bar{X}) = \Theta_R \cdot 2.5 \cdot k_{t,CFS} \cdot \omega_b \cdot \alpha_b \cdot f_u \cdot d \cdot t - \Theta_E \cdot (P_{E,G} + P_{E,Q}) \\ = 0$$

- Variations of the limit state function → depend on CFS thickness (t):

$$t < 2.5 \text{ mm}$$

$$g_{2-1}(\bar{X}) = \Theta_R \cdot 2.5 \cdot \frac{0.8 \cdot t + 1.5}{2.5} \cdot 0.55 \cdot \left(\frac{30}{d}\right)^{0.5} \cdot f_u \cdot d \cdot t - \Theta_E \cdot (P_{E,G} + P_{E,Q}) = 0$$

$$t \geq 2.5 \text{ mm}$$

$$g_{2-2}(\bar{X}) = \Theta_R \cdot 2.5 \cdot \frac{0.85 \cdot t + 0.55}{t} \cdot 0.55 \cdot \left(\frac{30}{d}\right)^{0.5} \cdot f_u \cdot d \cdot t - \Theta_E \cdot (P_{E,G} + P_{E,Q}) = 0$$

7. Reliability assessment of analytical models

Basic variables - Resistance

Variable	Symbol	Distribution	Mean μ_x	Standard deviation σ_x	Unit
Thickness of CFS section	t	Normal	1.98	0.05	mm
			2.97	0.07	
Diameter of the bolt	d	Normal	11.88	0.30	mm
			15.84	0.40	
Characteristic ultimate tensile strength of the CFS section	f_u	Log-normal	409.26	26.60	N/mm ²
Characteristic compressive cylinder strength of concrete	f_{ck}	Log-normal	24.8	2.48	N/mm ²
			29.8	2.98	
			34.8	3.48	
			44.8	4.48	
Overall nominal height of the shear connector	h_{sc}	Normal	94.05	0.94	mm
Mean width of the rib	b_0	Normal	118.8	1.18	mm
Width of the top flange of the profiled steel sheeting	b_1	Normal	89.1	0.89	mm
Overall depth of the profiled steel sheeting	h_p	Normal	59.4	0.59	mm
Model uncertainty factor for resistance - concrete failure	Θ_R	Normal	1.00	0.03	-
Model uncertainty factor for resistance - bearing failure	Θ_R	Normal	1.00	0.04	-

7. Reliability assessment of analytical models

Basic variables - Load

- Applied loads in this thesis:

- Considered: dead load (G) and live load (Q)
- Shear load:

$$P_E = P_{E,G} + P_{E,Q} = \gamma_G \cdot G_n + \gamma_Q \cdot Q_n$$

- Partial factors (EN 1990):

- $\gamma_G = 1.35$ for dead load
- $\gamma_Q = 1.5$ for live load
- Live loads ($Q_n = 2 \text{ kN/m}^2$) taken for office spaces (EN 1991-1-1, Category B)
- Dead load nominal value $G_n = 1 \text{ kN/m}^2$

- Load combinations:

- Ratio :

$$r = \frac{Q_n}{G_n + Q_n}$$

7. Reliability assessment of analytical models

Basic variables - Load

- Load combinations:
 - Ratio :

Loads	Ratio of the nominal live load to the total applied load r							
	0.3	0.4	0.5	0.6	0.66	0.7	0.75	0.8
Dead load	G_n	G_n	G_n	G_n	G_n	G_n	G_n	G_n
Live load	$0.21 Q_n$	$0.33 Q_n$	$0.5 Q_n$	$0.75 Q_n$	Q_n	$1.16 Q_n$	$1.5 Q_n$	$2.00 Q_n$

- Statistical parameters:

Variable	Symbol	Distribution	Mean μ_x	Standard deviation σ_x	Unit
Dead load	G	Normal	G_n	$0.1 \mu_x$	kN/m^2
Live load	Q	Gumbel	$0.6 Q_n$	$0.35 \mu_x$	kN/m^2
Model uncertainty factor for action effects	Θ_E	Normal	1.00	0.05	-

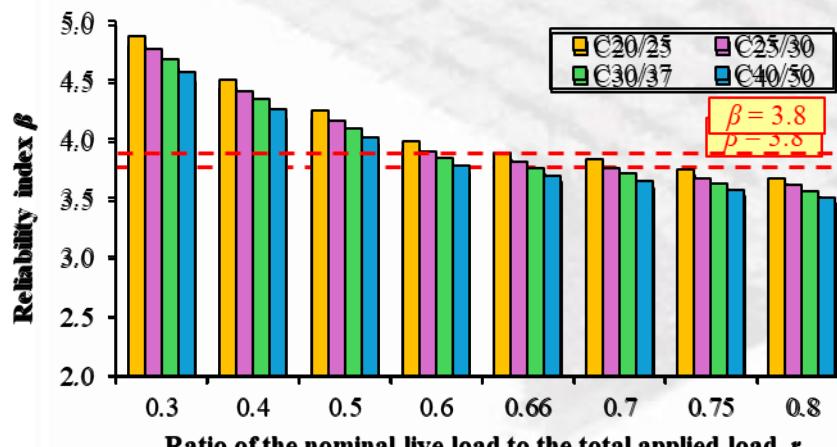
- Correction factor ζ :
 - Ensures ULS equilibrium condition $Z = R - \zeta E = 0$
 - Defined as $\zeta = R/E$
 - Treated as constant within model validity domain

7. Reliability assessment of analytical models

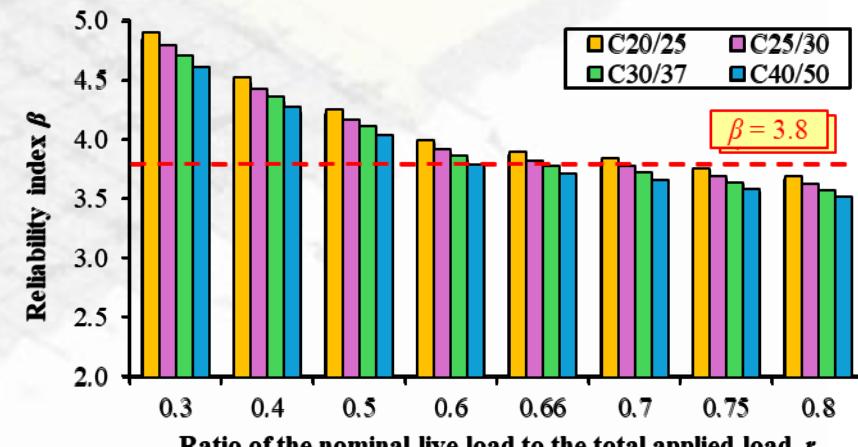
Reliability index – Concrete failure

- Results for $\gamma_V = 1.14$

- Reliability index β (computed) with COMREL-TI using FORM
- lowest $\beta = 3.47$ (live load dominant)
- M12 bolts give slightly lower β than M16 (FEM + analytical models)
 - Standard $\gamma_V = 1.25$ (EN 1993-1-3, EN 1994-1-1)



$t = 3 \text{ mm}$, $d = 12 \text{ mm}$

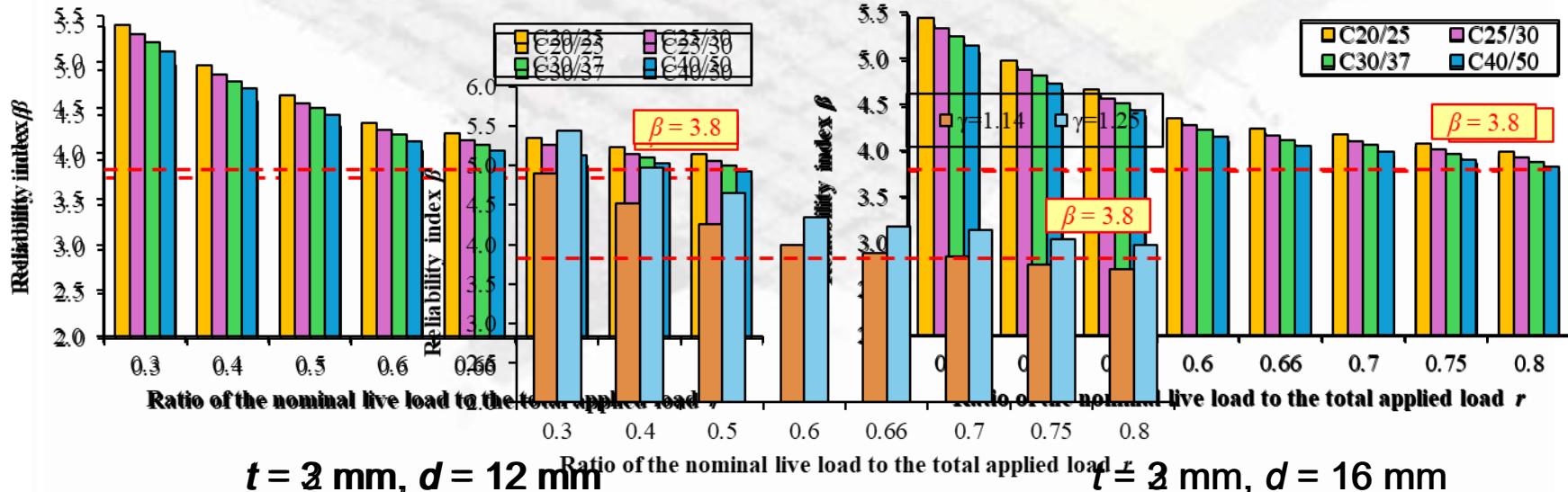


$t = 3 \text{ mm}$, $d = 16 \text{ mm}$

7. Reliability assessment of analytical models

Reliability index – Concrete failure

- Results for $\gamma_V = 1.25$
 - All β -values > 3.80 across load ratios
 - Even at extreme $r = 0.8$ (live load twice dead load), reliability remains above requirement
- Comparison of $\gamma_V = 1.14$ vs. $\gamma_V = 1.25$
 - $\gamma_V = 1.25 \rightarrow$ consistently higher β (expected, due to stronger safety margin)
 - Both factors ensure sufficient reliability; $\gamma_V = 1.25$ fully covers all scenarios

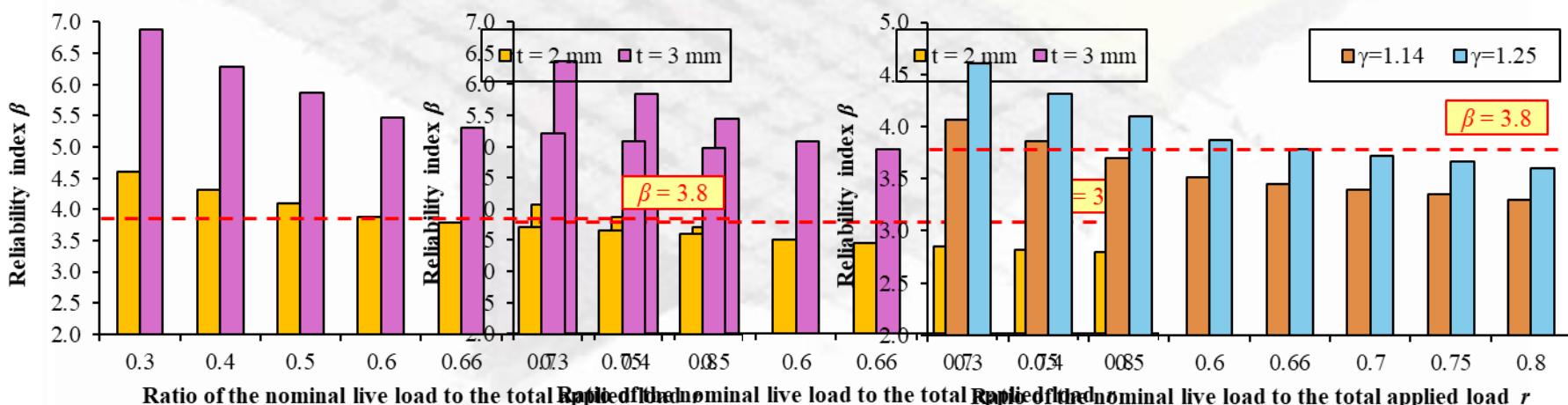


7. Reliability assessment of analytical models

Reliability index – Bearing failure

- Results of $\beta_{M2} = 1.25$

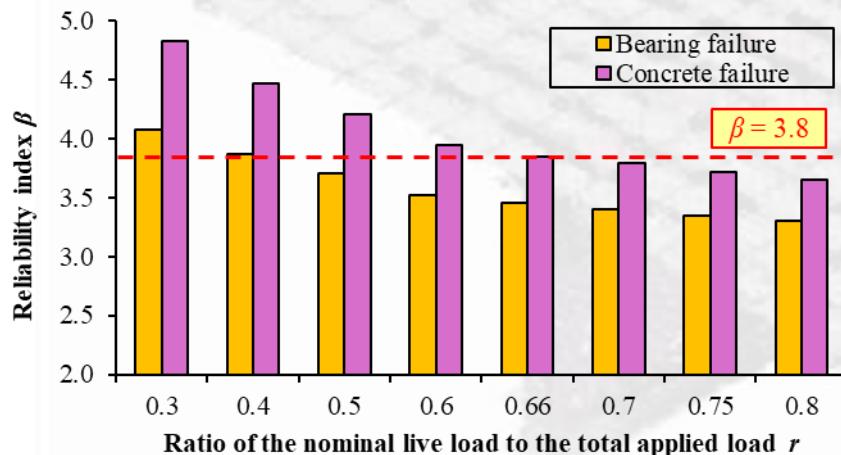
- Reliability index based on $\gamma = 1.14$ ($\beta_{M2} = 0.8$, live load dominant)
- Reliability index based on $\gamma = 1.25$ ($\beta_{M2} = 1.14$ (fairly good) and $\beta_{M2} = 1.25$ (Eurocode))
- Considered tolerances: 3 mm (high probability of stability) and 2 mm and 3 mm
- 3 mm CFS → higher β , bearing failure unlikely to govern



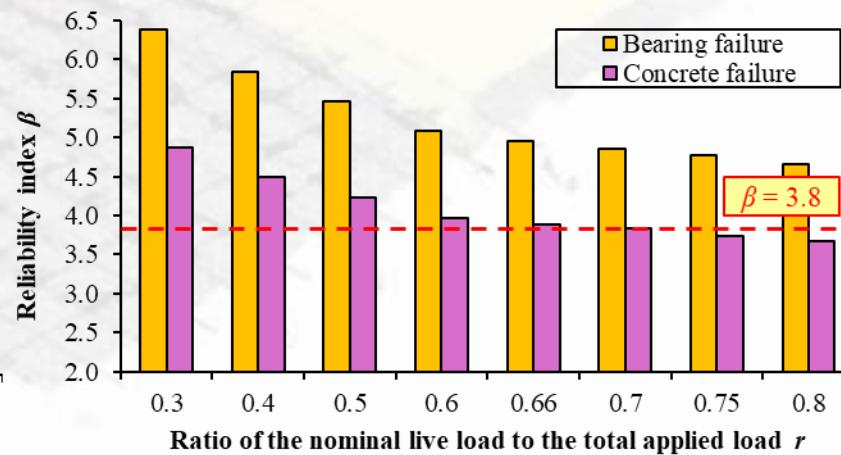
7. Reliability assessment of analytical models

Reliability index – Concrete vs. Bearing failure

- Methodology:
 - Reliability index β computed with FORM
 - Global partial safety factors: $\gamma_{M2} = 1.14$ (proposed) and $\gamma_{M2} = 1.25$ (Eurocode)
 - Models evaluated for M12 bolts with CFS thicknesses 2 mm and 3 mm



$t = 2 \text{ mm}, d = 12 \text{ mm}$

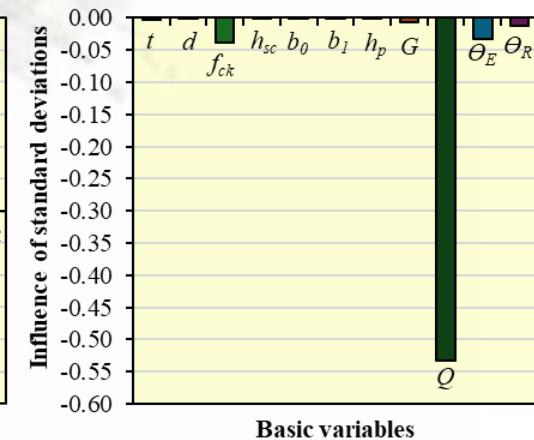
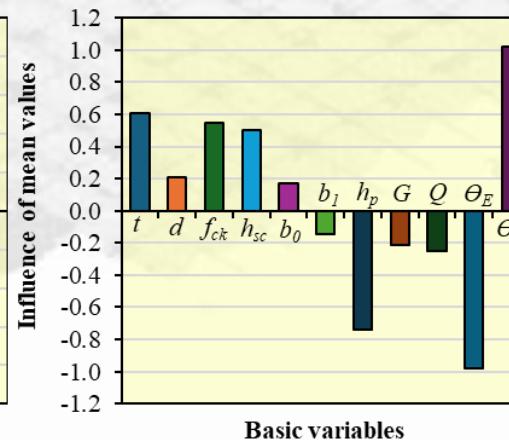
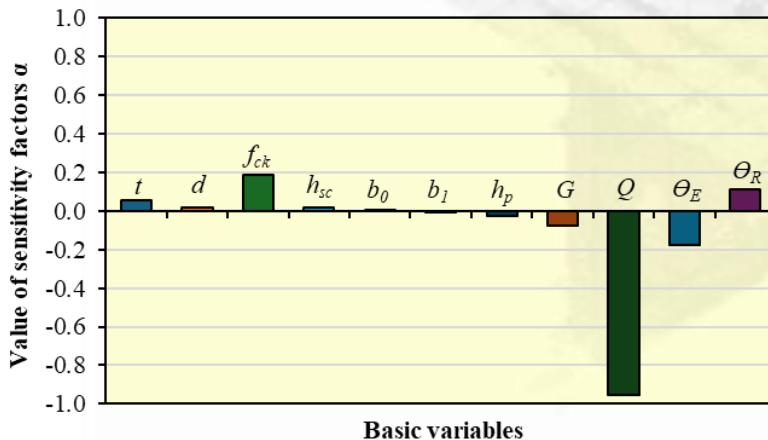


$t = 3 \text{ mm}, d = 12 \text{ mm}$

7. Reliability assessment of analytical models

Sensitivity Analysis of Basic Variables and Reliability Index

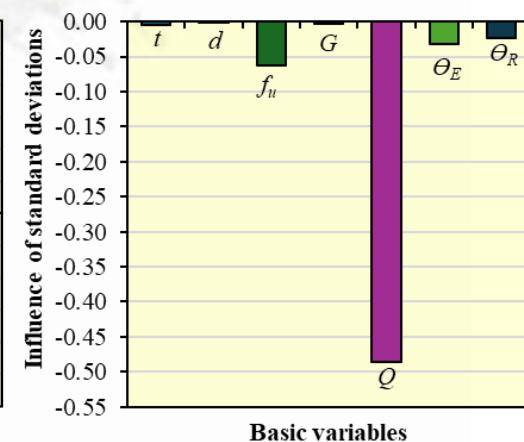
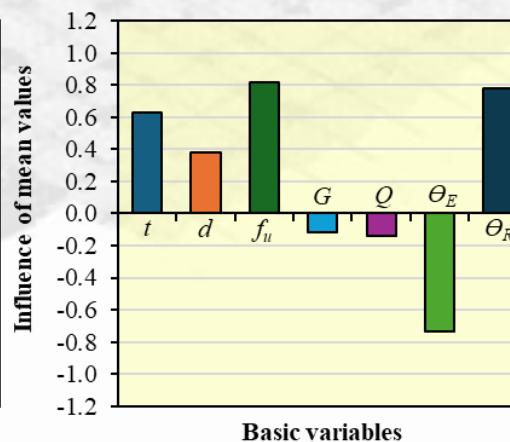
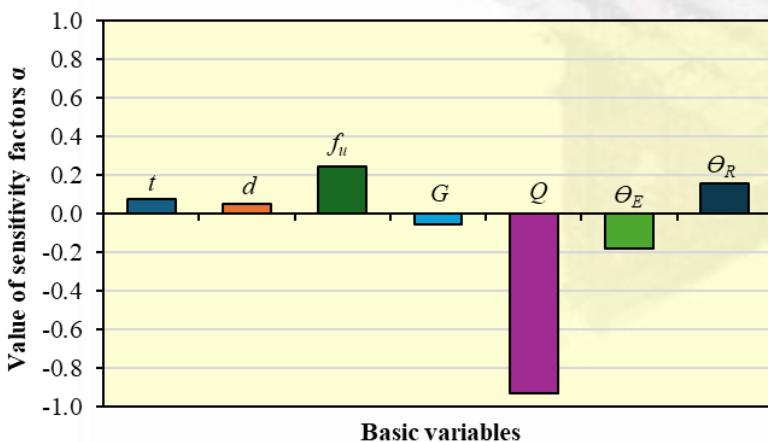
- Definition of sensitivity factors for variables for concrete failure:
 - Mean values (μ) and standard deviations (σ) of variables for reliability index (θ_E)
 - Shear connector height (h_p), sheet depth (b_0)
 - Accurate estimation of f_{ck} and geometric dimensions is critical
- Most influential action variables:
 - High sensitivity of mean and variability of service load (Q) highlights the importance of proper load characterization
 - Measures how θ_E responds to changes in mean values (μ) and standard deviations (σ) of variables
 - Helps identify critical parameters affecting failure mechanisms



7. Reliability assessment of analytical models

Sensitivity Analysis of Basic Variables and Reliability Index

- Most influential resistance variables:
 - CFS thickness (t), bolt diameter (d), tensile strength of CFS (f_u)
- Most influential action variables:
 - Live load (Q)
- Observations:
 - Proper control of CFS geometry, bolt size, and steel quality is essential
 - Mean value of f_u significantly affects reliability



8. Conclusion and future work

8. Conclusion and future work

Scientific Contributions

1. Nonlinear numerical models developed using the finite element method and validated based on experimental tests results.
2. Identified failure mechanisms and the dependence of key parameters on the behaviour of the bolted shear connection in composite CFS–concrete systems.
3. Developed analytical procedure for the shear connection resistance calculation of the composite CFS-concrete system.
4. Probabilistically validated and established a reliable proposed analytical procedure for determination the shear connection resistance.

8. Conclusion and future work

Main Conclusions

- **Structural Behaviour**
 - Demountable bolted shear connections in CFS-concrete beams exhibit complex shear behaviour due to thin CFS sections
 - Shear resistance and ductility depend on the interaction of multiple deformation patterns
- **Failure Mechanisms**
 - Three primary failure modes identified
 - Concrete pry-out → conical cracking and crushing
 - Bolt shear and bending failure
 - Bolt hole bearing failure in CFS section → hole elongation and nut inclination
- **Failure mode depends on CFS thickness:**
 - $t < 3 \text{ mm}$ → bolt hole bearing dominates
 - $t \geq 3 \text{ mm}$ → concrete pry-out dominates
- **Influence of Key Parameters**
 - CFS thickness:
 - Increases shear capacity up to a threshold ($\sim 3 \text{ mm}$)

8. Conclusion and future work

Main Conclusions

- **Influence of Key Parameters**
 - Bolt diameter:
 - Larger diameters consistently improve shear resistance
 - Concrete strength:
 - Higher f_{ck} shifts failure from concrete pry-out to bolt/CFS interaction
 - Must balance strength for ductility
 - Bolt embedment height:
 - Greater height increases resistance
 - Important for analytical predictions
 - Profiled steel sheeting geometry:
 - Depth relative to slab thickness significantly influences shear resistance
 - Material quality:
 - Proper selection and quality control of CFS profile, bolts, and concrete are crucial
 - Lightweight concrete:
 - Slightly reduces shear capacity
 - optimising f_{ck} mitigates effect

8. Conclusion and future work

Main Conclusions

- **Influence of Key Parameters**

- Slab type:
 - Solid slabs → higher shear resistance and sensitivity to bolt diameter
 - Profiled slabs → more uniform performance across bolt sizes

- **Analytical Models**

- Provided formulas for:
 - Concrete pry-out resistance

$$P_{c,Rd} = \frac{20 \cdot \alpha_{CFS} \cdot \alpha_c \cdot d^2 \left(f_{ck} \cdot \frac{h_{sc}}{d} \right)^{0.5}}{\gamma_V}$$

CFS bolt hole bearing resistance

$$F_{b,Rd} = \frac{2.5 \cdot k_{t,CFS} \cdot \omega_b \cdot \alpha_b \cdot f_u \cdot d \cdot t}{\gamma_{M2}}$$

- Analytical models accurately predict shear resistance for identified failure mechanisms

- **Reliability Analysis**

- Global partial safety factor $\gamma_V = \gamma_{M2} = 1.14$ ensures $\beta \geq 3.8$ under typical load conditions ($r = 0.3-0.7$)
- Minimum β for extreme live-load-dominated case ($r = 0.8$): 3.47 (concrete), 3.30 (bearing) → acceptable due to ductile failure

8. Conclusion and future work

Main Conclusions

- **Reliability Analysis**

- Increasing γ_{M2} to 1.25 increases reliability but may lead to more conservative and material-costly designs
- Sensitivity analysis:
 - Thickness of CFS, bolt diameter and concrete strength are the most influential parameters
 - Accurate characterization of service load Q (mean and variability) is critical

8. Conclusion and future work

Recommendations for future work

- **Extended validation:** Perform additional push-out tests to verify the analytical models and failure criteria, exploring variations in geometry, loading, and material properties to cover wider real-world conditions
- **Ductility optimisation:** Study coordinated selection of components to ensure ductile behaviour and develop design recommendations for practical applications
- **Connection comparison:** Evaluate bolted CFS–concrete connections against other types and traditional solutions based on resistance, ductility, failure modes, and practical factors like weight, cost, and assembly efficiency

Project title: Innovative lightweight cold-formed steel-concrete composite floor system

Acronym: LWT-FLOOR Project ID: UIP-2020-02-2964

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Thank you for attention!

Reliability of shear connection in cold-formed steel-concrete composite system

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