# Analysis of Demountable Shear Connections in Cold-formed Steel-Concrete Composite Beams: A Finite Element Approach Validated With Experimental Data

**Vlaho Žuvelek** | **Ivan Ćurković** | **Ivan Lukačević** | **Andrea Rajić**
**vlaho.zuvelek@grad.unizg.hr**

LWT–FLOOR
RESEARCH PROJECT

HRZZ Croatian Science Foundation

ICSAS 2024
10th International Conference on Steel and Aluminium Structures
5-7 June 2024
Rio de Janeiro, Brazil

# Agenda

- Introduction
- Experimental study
- Finite element (FE) model
  - Geometry, boundary conditions and loading
  - Mesh, interactions and analysis method
  - Material characteristics
  - Validation of FE models
- Parametric study
- Results and discussion
- Conclusion

# 1. Introduction

## Composite steel-concrete structural systems

**Cost Effectiveness**

Most cost-effective construction systems

**Efficiency & Speed**

Structural efficiency
Accelerated construction speed

**Steel**

High tensile strength and ductility

**Concrete**

High stiffness and compressive strength

# 1. Introduction

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

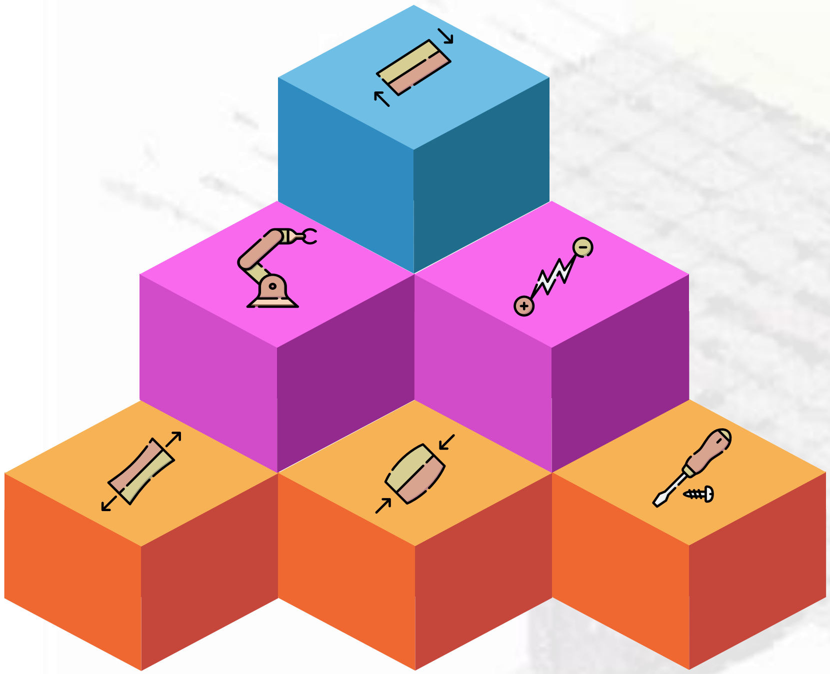
### Continuous Development

Composite steel-concrete systems remain a field of continuous development

### Material Efficiency

Growing tendency to reduce material usage while enhancing performance

# 2. Experimental study



### Phase 1

Base material:

- CFS sheets
- bolts
- concrete
- reinforcement mesh

### Phase 2

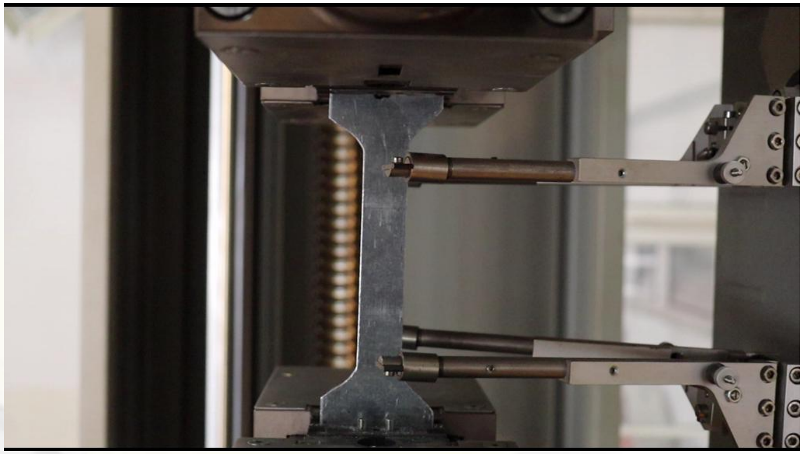
Investigation the resistance of spot welds

### Phase 3

Testing push-out specimens

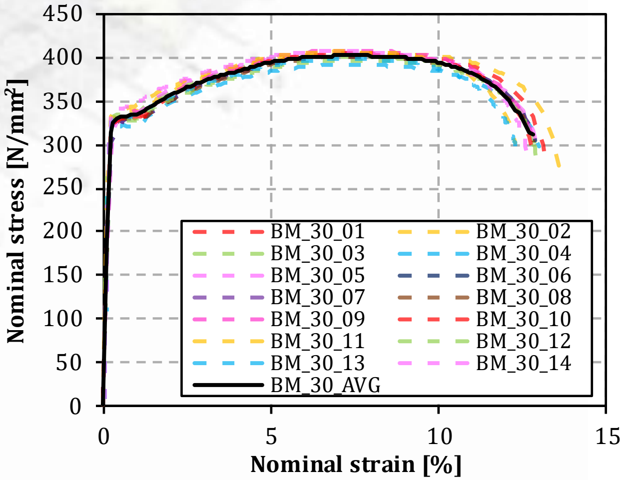
# Phase 1

## 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

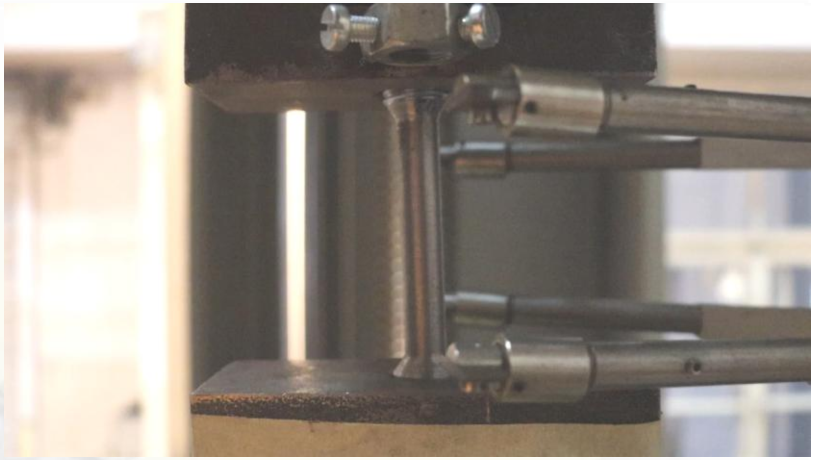


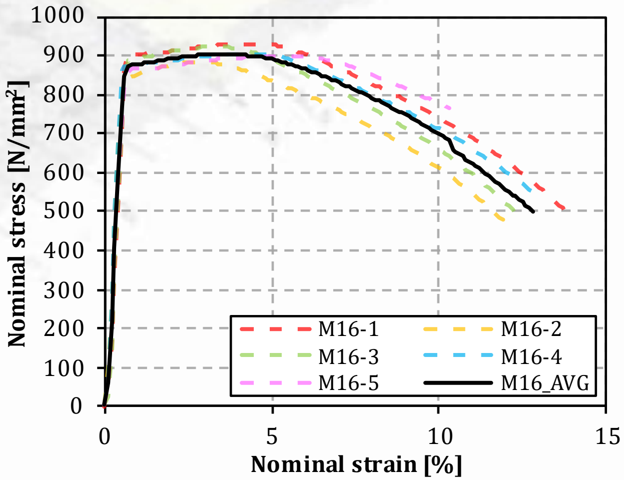
# 2. Experimental study

## Phase 1

01. CFS sheets

02. Bolts





# Phase 1

01. CFS sheets

02. Bolts

03. Concrete


| | $f_{cm}$ [MPa] | $E_{cm}$ [MPa] |
|---|---|---|
| Mean value | **28.09** | **29526** |
| St. dev. [%] | 2.429 | 0.281 |
| CoV[%] | 8.64 | 0.95 |

# 2. Experimental study

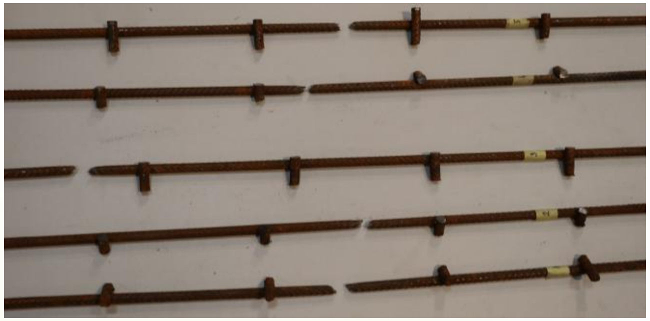
## Phase 1

01. CFS sheets

02. Bolts

03. Concrete

04. Reinforcement mesh



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

## Phase 2

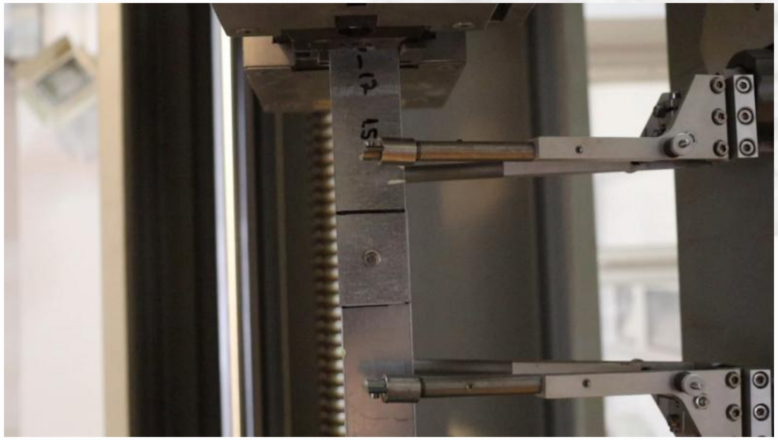
Combination of sheet thicknesses for spot welds:

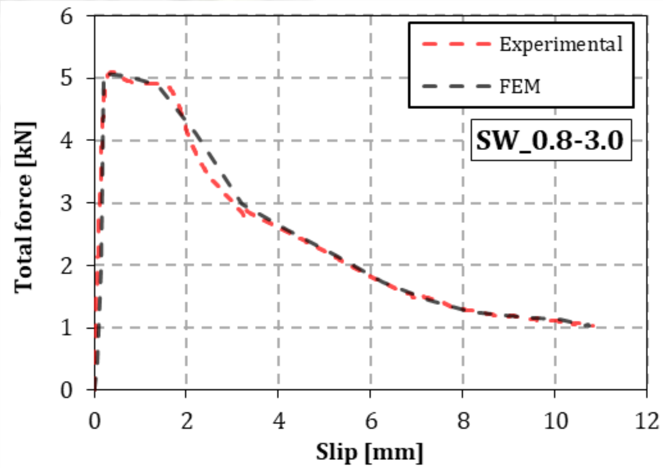
- 0.8 mm – 0.8 mm
- 0.8 mm – 1.0 mm
- 0.8 mm – 1.25 mm
- 0.8 mm – 1.5 mm
- 0.8 mm – 2.0 mm
- 0.8 mm – 2.5 mm
- 0.8 mm – 3.0 mm
- 1.0 mm – 1.0 mm
- 1.0 mm – 1.25 mm
- 1.0 mm – 1.5 mm
- 1.0 mm – 2.0 mm
- 1.0 mm – 2.5 mm
- 1.0 mm – 3.0 mm
- 1.25 mm – 1.25 mm
- 1.25 mm – 1.5 mm
- 1.25 mm – 2.0 mm
- 1.25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

# 2. Experimental study

## Phase 2

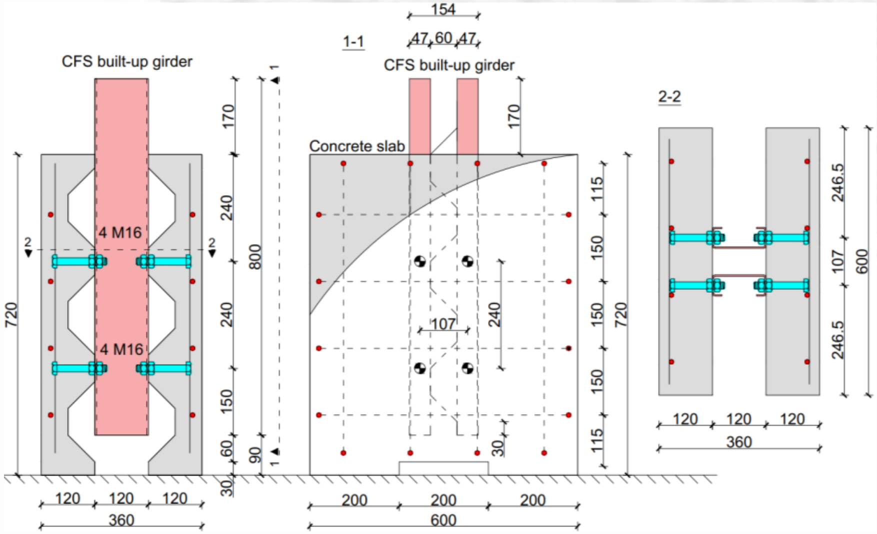





## Phase 3

Idea and design of push-out specimens:

- CFS 120x47x3 mm
- Concrete slab 720x600x120 mm
- Profiled steel sheeting 720x600x1.0 mm
- Corrugated web 780x120x1.25 mm
- Bolts M16, steel grade 8.8




# 2. Experimental study

## Phase 3

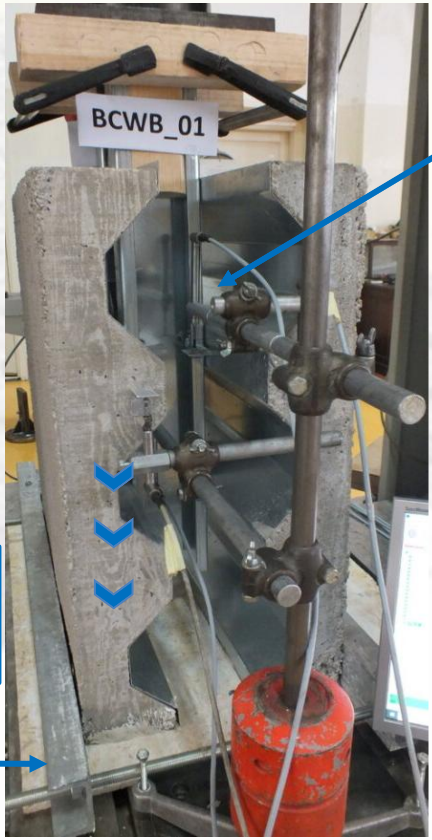
Fabrication process of bolted shear connection specimens

# Phase 3

Test setup for push-out specimens

Stiffeners

LVDT sensors
(8 pieces)




Indentation of the concrete slab

Stiffeners

# 2. Experimental study

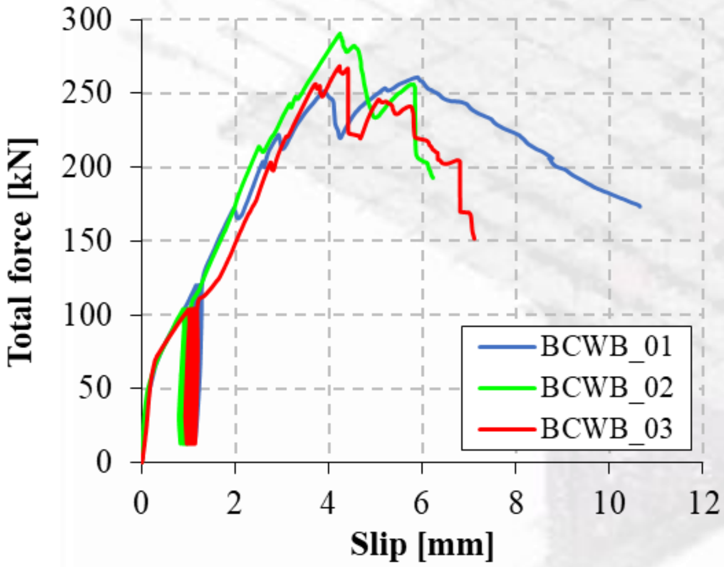
## Phase 3

Test setup for push-out specimens

## Phase 3

### Analysis and processing of results

- The statistical evaluation of experimental results according to EN 1990 - Annex D and EN 1994-1-1

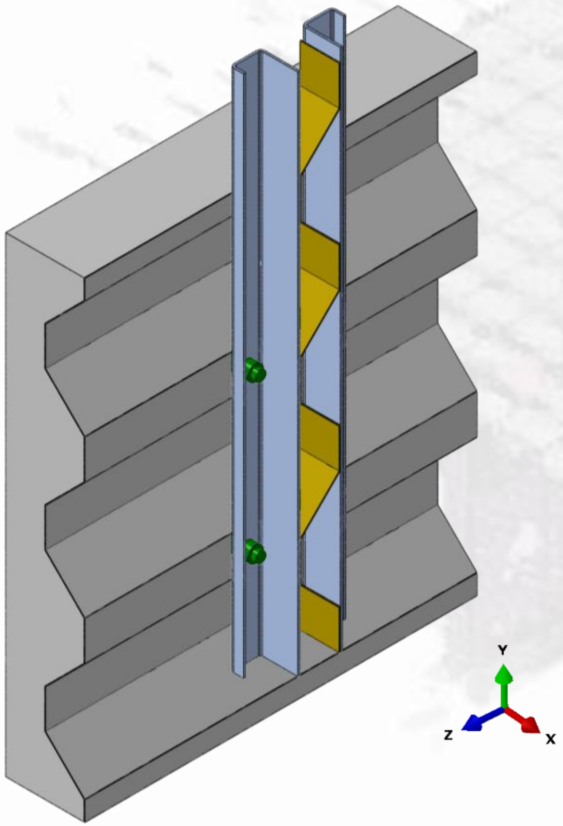


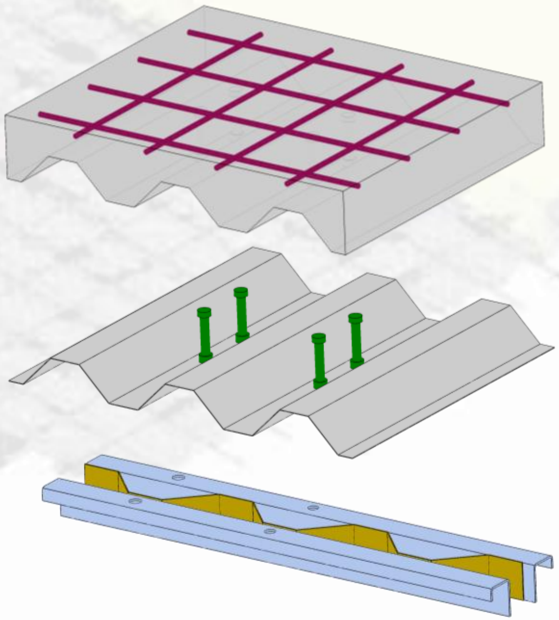

| Specimen | Ultimate force $P_{ult}$ [kN] | Slip $\delta_u$ [mm] | Stiffness $k_{sc}$ [kN/mm] |
|---|---|---|---|
| BCWB_01 | 260.9 | 7.31 | 78.5 |
| BCWB_02 | 290.5 | 5.84 | 86.2 |
| BCWB_03 | 268.4 | 5.80 | 73.4 |
| Mean | **273.3** | **6.32** | **79.4** |
| St. Deviation | 15.39 | 0.86 | |
| CoV [%] | 5.63 | 13.62 | |
| Characteristic | 226.3* (234.8**) | 4.03* (5.22**) | |

Note: * according to EN 1990: 2010 ; ** according to EN 1994-1-1:2004

# 3. Finite element (FE) model

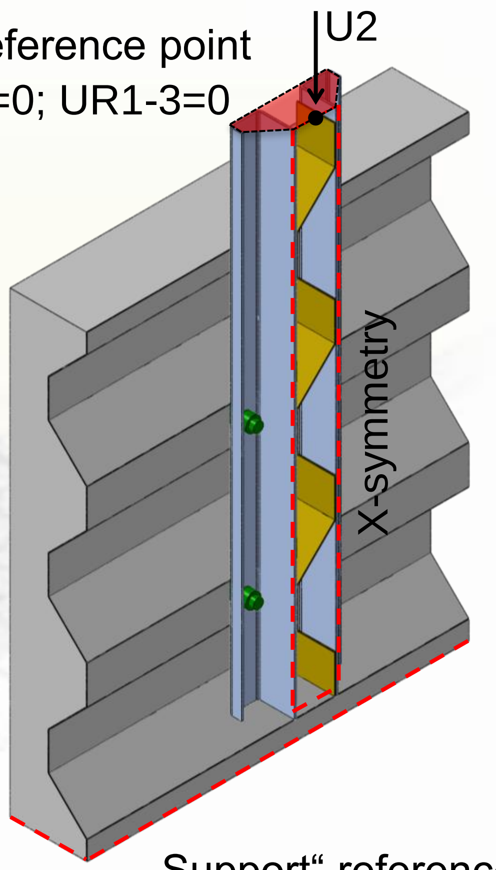
- Abaqus Explicit solver (quasi – static analysis)
  - To address geometrical and material nonlinearities
- Bolted shear connection (embedded nuts)
  - Increased stiffness
  - Easier mounting



# 3. Finite element (FE) model

- 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

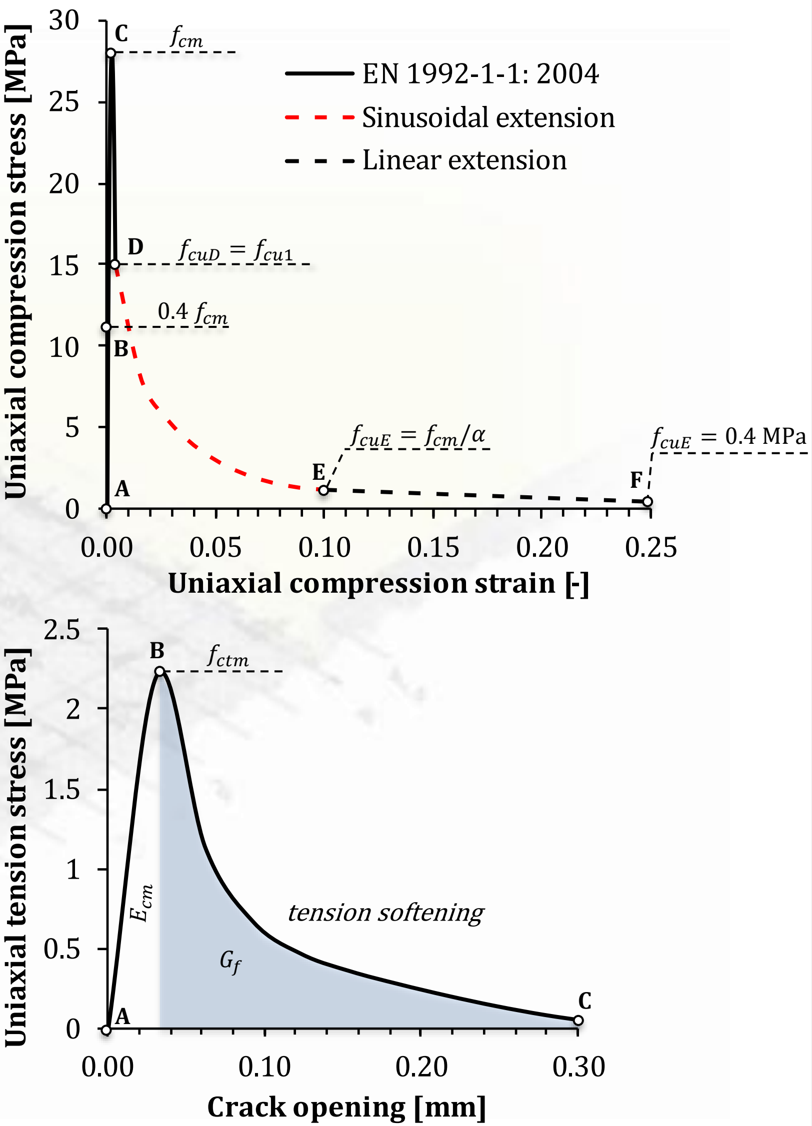


# 3. Finite element (FE) model

- Interaction
  - Normal behaviour
    - Hard contact
  - Tangential behaviour
    - Penalty friction (0.1, 0.2, 0.3 and 0.7 frictional coefficient)
  - Spot welds
    - Bushing type connectors
    - Elasticity, Plasticity, Damage and Failure characteristics

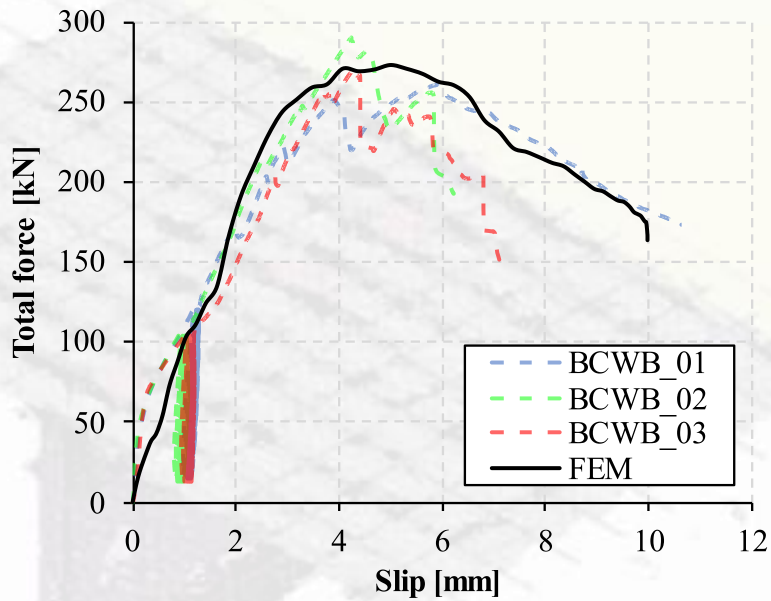
# 3. Finite element (FE) model

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



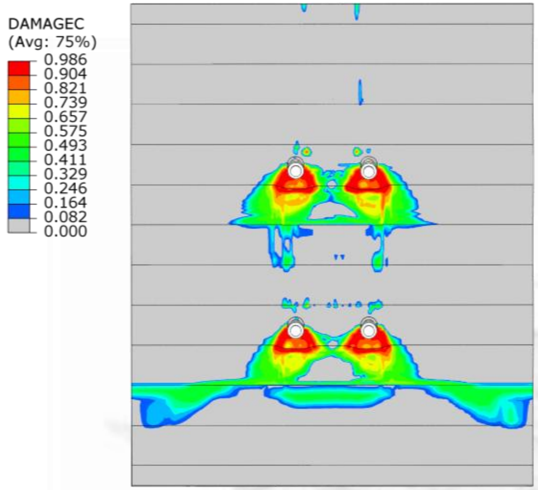
# 3. Finite element (FE) model

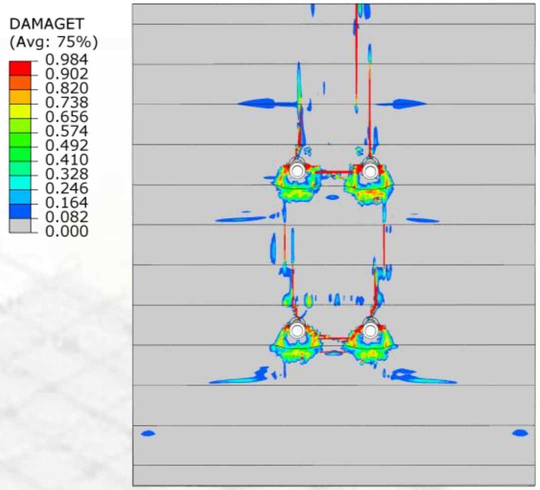
- Validation of numerical models
  - Good agreement between experimental and numerical simulation
  - Benchmark model for parametric analyses

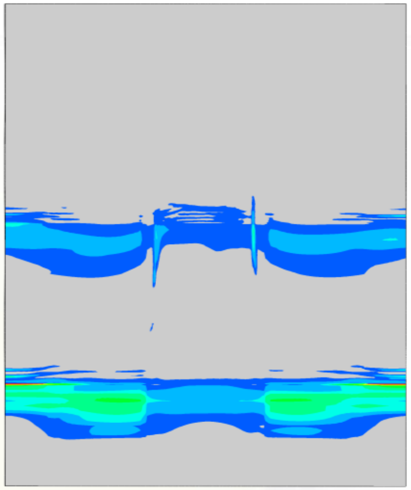


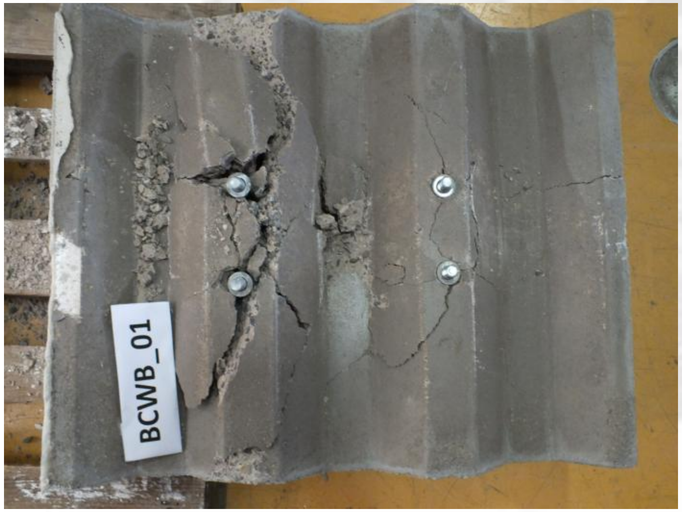

| Specimen | Ultimate force | | | Slip | | |
|---|---|---|---|---|---|---|
| | $P_{ult,\,Exp}$ [kN] | $P_{ult,FEM}$ [kN] | Ratio | $\delta_{u,Exp}$ [mm] | $\delta_{u,FEM}$ [mm] | Ratio |
| BCWB_01-03 | 273.3 | 273.3 | **1.00** | 6.32 | 6.67 | **0.95** |

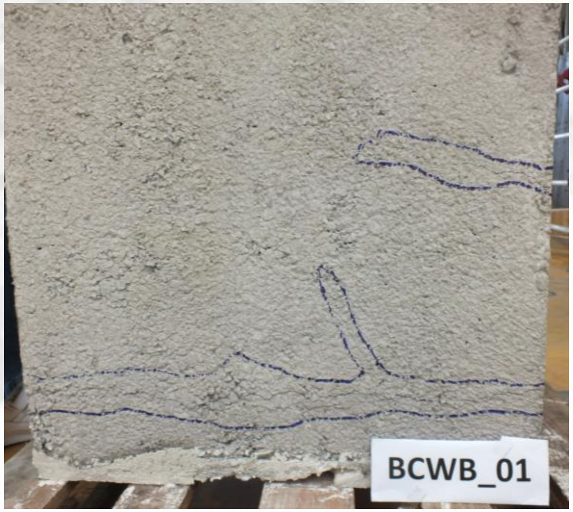
# 3. Finite element (FE) model

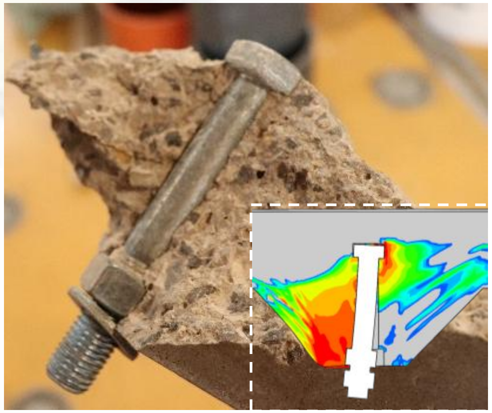




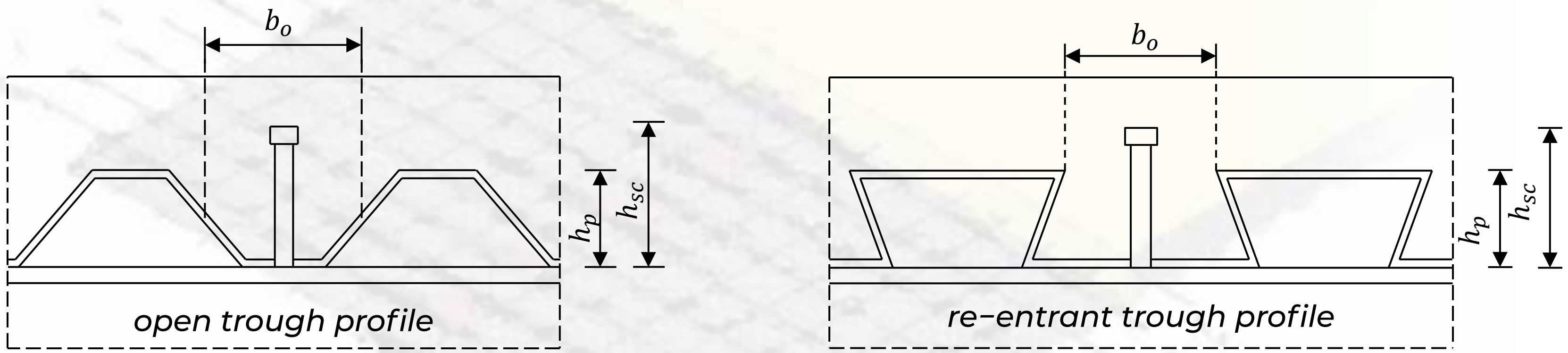



Crushing of concrete (cone failure) and development of tensile cracks

# 4. Parametric study

- Varied width ($b_o$) and height ($h_p$) of concrete rib across 12 parametric models
- Objective:
  - Investigate influence of different geometries and types of profiled sheeting on ultimate capacity of bolted shear connectors.



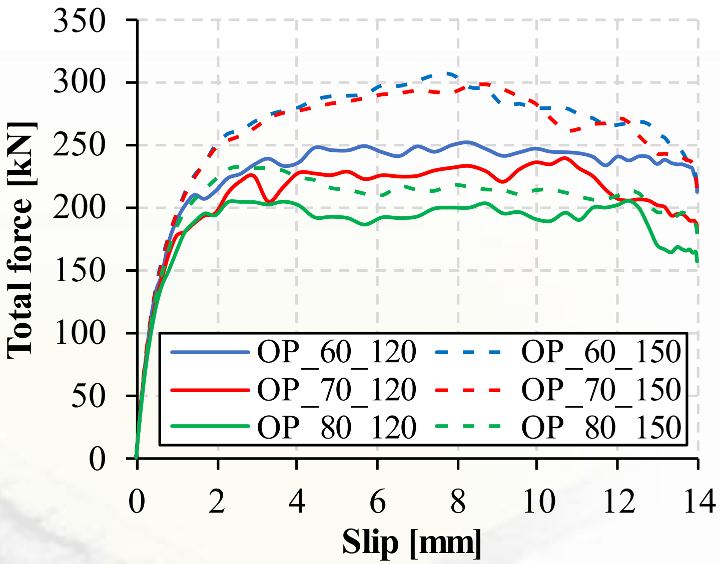

Height of the concrete rib $h_p$ :
60, 70 and 80 mm

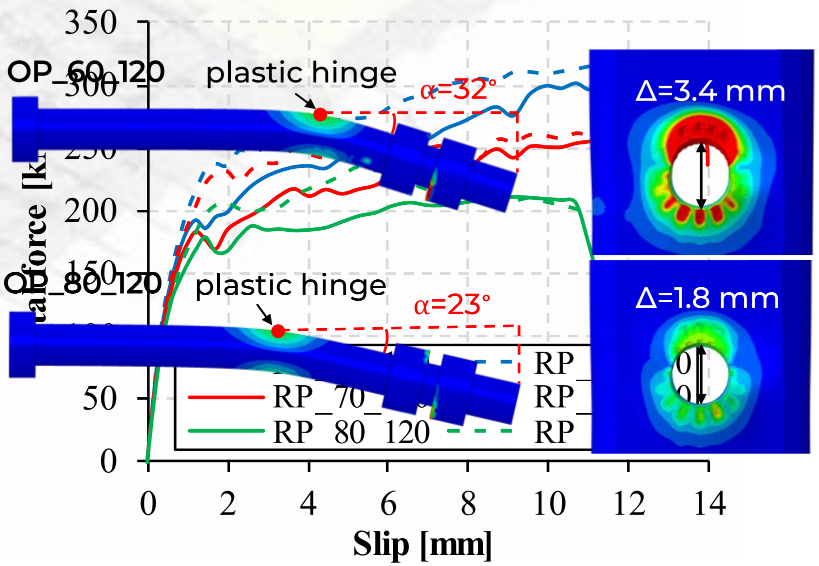
Type of profiled steel sheeting:
OP = open trough
RP = re-entrant trough

OP_60_120

Width of the concrete rib $b_o$ :
120 and 150 mm

- Complex behaviour of CFS elements leads to an interaction between multiple failure modes
- Lower concrete rib heights exhibit better shear behavior and resistance compared to higher rib heights in the models
- Different rib heights result in varying shear force distributions
- Slightly better shear resistance observed in certain models with a re-entrant trough profile (RP)



# 5. Results and discussion

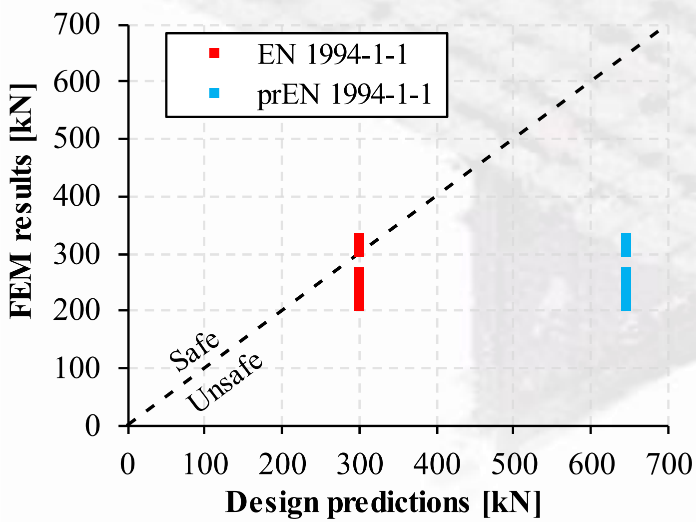
- The results of the parametric analysis are presented in Table
- All models fulfil ductility classification according to EN 1994-1-1

| Models | Ultimate force [kN] | Ductility | Failure mode | Models | Ultimate force [kN] | Ductility | Failure mode |
|---|---|---|---|---|---|---|---|
| OP_60_120 | 253.2 | Ductile | B-Y-C | RP_60_120 | 306.5 | Ductile | B-Y-C |
| OP_60_150 | 307.1 | Ductile | B-Y-C. | RP_60_150 | 324.2 | Ductile | B-Y-C |
| OP_70_120 | 237.7 | Ductile | B-Y-C. | RP_70_120 | 266.8 | Ductile | B-Y-C |
| OP_70_150 | 298.8 | Ductile | B-Y-C | RP_70_150 | 265.1 | Ductile | B-Y-C |
| OP_80_120 | 205.2 | Ductile | B-Y-C. | RP_80_120 | 211.1 | Ductile | B-Y-C |
| OP_80_150 | 233.7 | Ductile | B-Y-C | RP_80_150 | 236.8 | Ductile | B-Y-C |

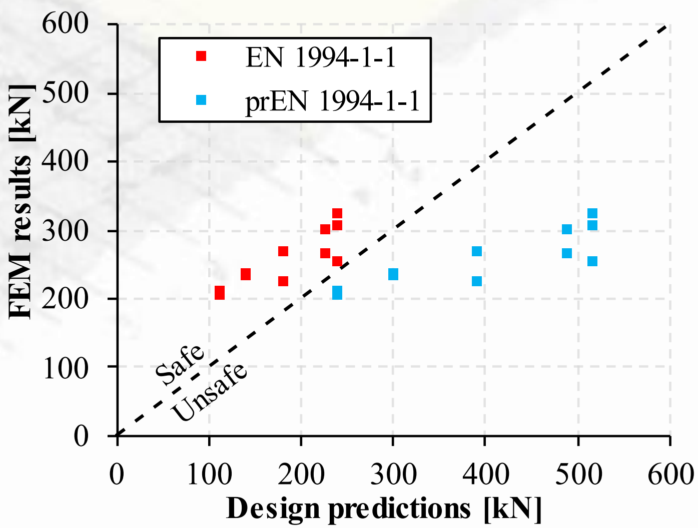
Note: B= bearing in steel sections; Y= yielding of bolts; C= concrete failure

# 5. Results and discussion

- The parametric analysis results were compared with the analytical predictions described in EN 1994-1-1 and prEN 1994-1-1
- Analytical predictions showed notably conservative and unconservative correlations
- Provide insight into the complex behaviour of the shear connection in composite CFS-concrete systems




with out factor reduction $k_t$




with factor reduction $k_t$

# 6. Conclusion

- The finite element approach revealed the complex behaviour of shear connections, highlighting the interaction between multiple failure modes that impacts the ultimate resistance of the shear connection.

- Models with a lower rib height exhibited higher shear connection capacity due to a larger volume capacity of the concrete and a more favourable interaction between failure modes, resulting in a stress distribution over several components.

- A comparison with analytical predictions indicated unreliability in predicting the shear resistance of composite CFS-concrete systems.

# Thank you for attention!

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