Behaviour and Design of Steel Cladding Systems under Combined Wind and Bushfire Conditions

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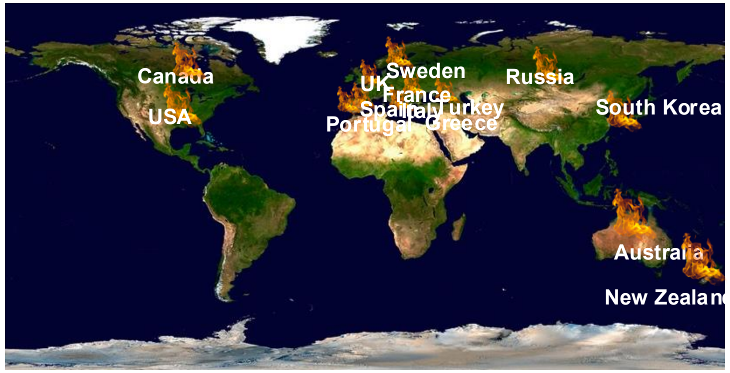
https://www.realestate.com.au/news/protect-property-bushfire/

Bushfires



Costliest natural disaster

Bushfires	Year	Deaths	No of destroyed homes	Burnt area (km^2)	Overall losses (AUD)
Black Friday	1939	71	700	20,000	-
Tasmanian Black Tuesday	1967	62	1400	2,600	35 million
Ash Wednesday	1983	75	2400	5,200	335 million
Black Saturday	2009	173	2000	4,500	1.7 billion
2019–20 Black Summer Bushfire	**2019 - 2020**	**34 (direct)**	**5900**	**186,000**	**≈ 2 billion**

- Strong winds
- Low humidity
- High temperature
- High fuel load

- Climate change
- Dense population at bushfire-urban interface
- Improper fuel and land management
- Less awareness of the risk
- Limited firefighting resources
- Structures not capable of withstanding fires

Bushfire Attack Mechanisms

1. Ember Attack:

- **Leading cause of house destruction (about 80%)**

2. Radiant Heat:

- Arises directly from the fire front or nearby combustion

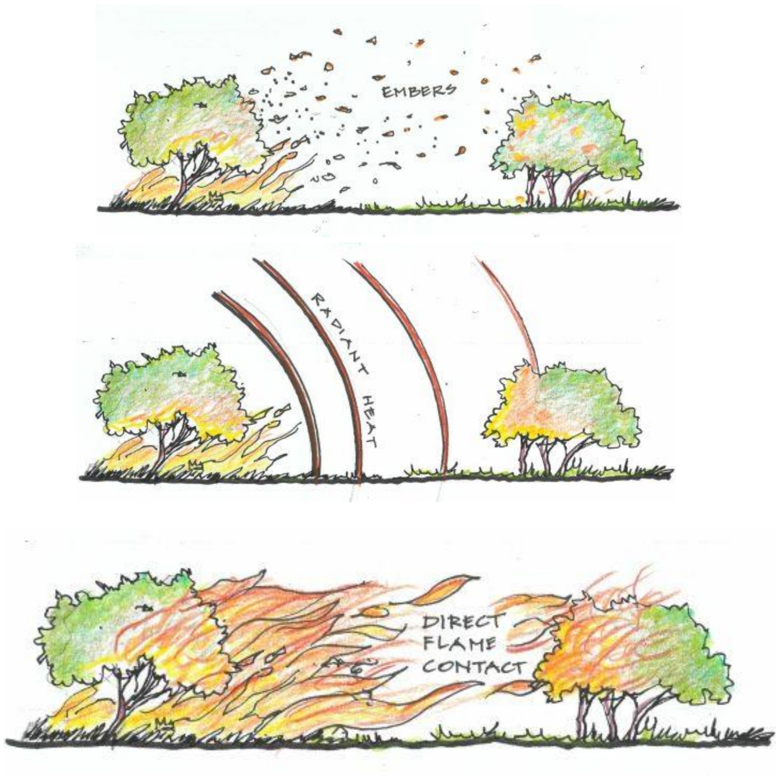
3. Flame front contact:

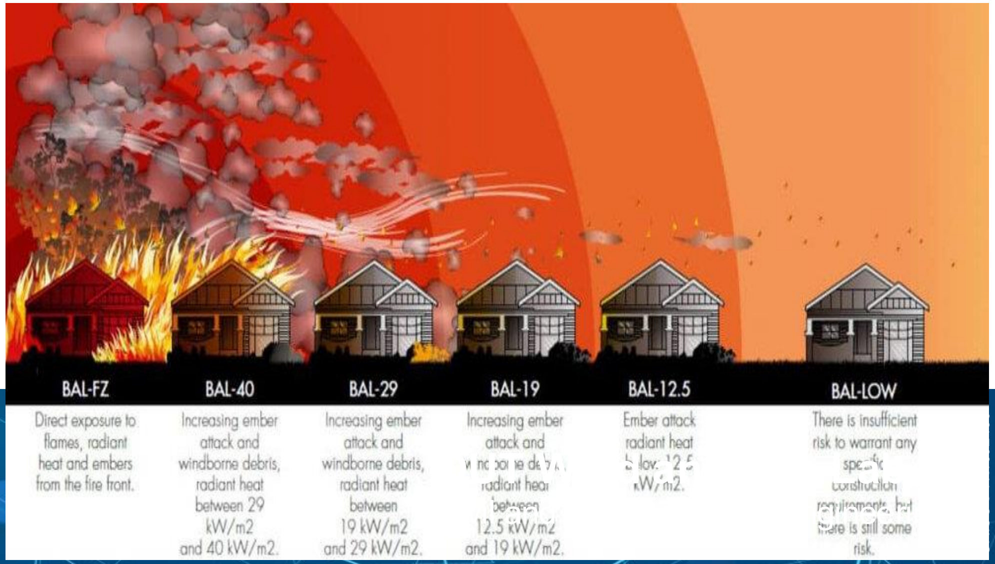
- This risk occurs when advancing flames engulf structures
- 85% of house losses occur within 100m of bushland

AS 3959 defines **bushfire attack level** (BAL) for the specific location depending on (BAL Low to BAL FZ):

- Type of vegetation
- Distance from vegetation
- Slope of the land (fire moves quicker upslope)
- Fire Danger Index (FDI)

It gives a *heat flux versus time curve* for *BAL12.5-40, and standard fire curve for BAL-FZ* for testing building products. Relies on non-combustible external envelope for ember attack



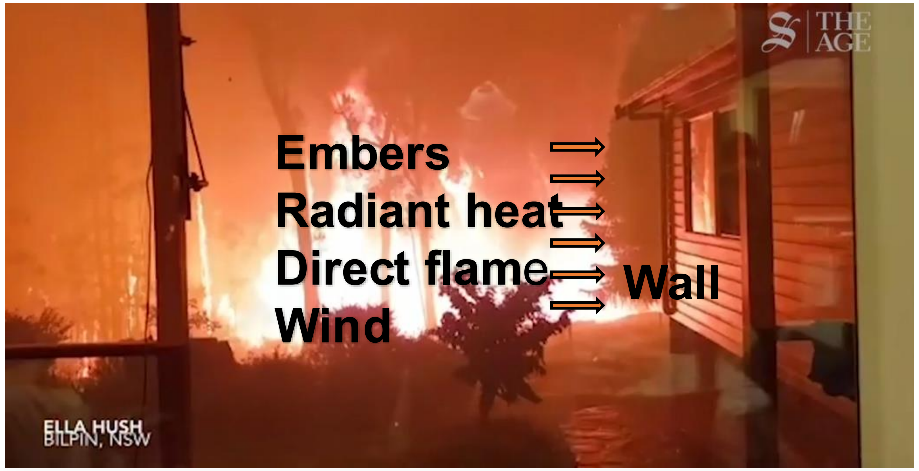


Bushfire-Enhanced Wind

- Bushfires generate strong winds

Bushfire-enhanced wind may lead to:

- Increased longitudinal wind velocity of >50%
- Increased wind pressure/suction by 25-150% on a building envelope
- Most significant fire-enhanced winds are experienced as the fire front approaches the buildings
- Fire-enhanced winds may lead to blowing off parts or entire building envelopes before the bushfire reaches the building – vulnerable after loss of external claddings for ember attack and direct flames!
- AS 3959 does not consider enhanced wind


THE AGE
Embers
Radiant heat
Direct flame
Wind
Wall
ELLA HUSH
BILPIN, NSW

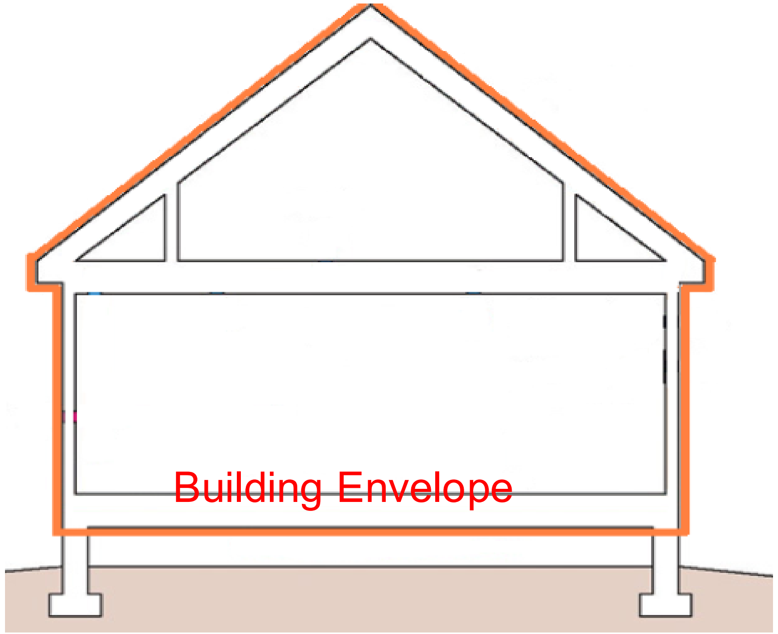

AP

Design and Construction of Buildings to withstand Bushfires

- Since bushfire and wind interact with buildings and landscape, we need site-specific solutions (well-designed & constructed and maintained).

- As recommended in AS3959 and NASH, the use of non-combustible cladding elements and systems (steel cladding, bricks, AAC panel etc) as external building envelope without any gaps larger than 2 mm will eliminate ember attack and reduce building damage.
- During bushfire events, gaps should not develop to larger than 2 mm under combined bushfire-enhanced wind action and high temperatures

- Building products should also withstand radiant heat and flame immersion.



Steel Cladding Building Envelope

Cold-formed steel roof and wall claddings are frequently used in low- and mid-rise buildings, and commonly utilized in bushfire prone areas

Advantages:

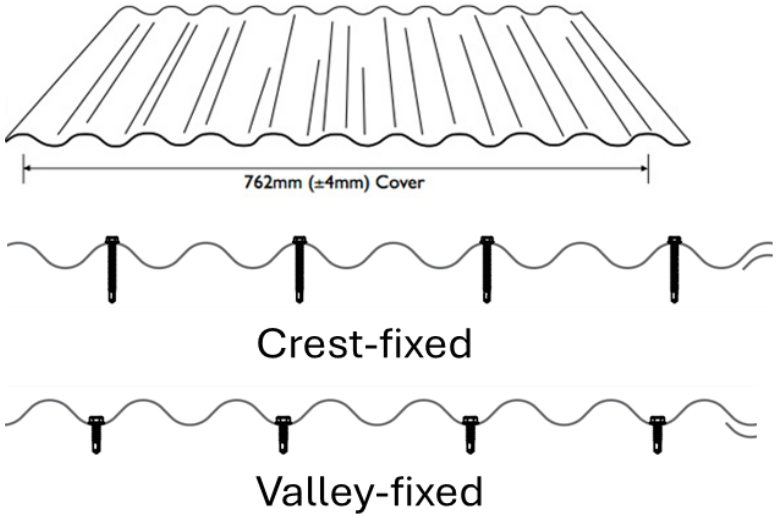
- Non-combustible
- Light-weight
- Higher strength and stiffness
- Simple installation and handling
- Cost-effective

Wind damage

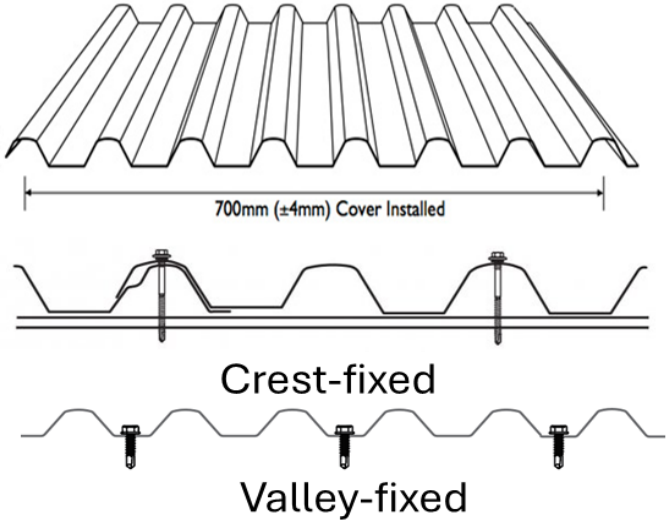
Commonly used CFS roof and wall cladding profiles:

- 0.42 mm or 0.48 mm thick G550 steel
- Corrugated claddings
- Trapezoidal claddings with closely spaced ribs
- Trapezoidal claddings with wide pans
- Crest-fixed and valley fixed

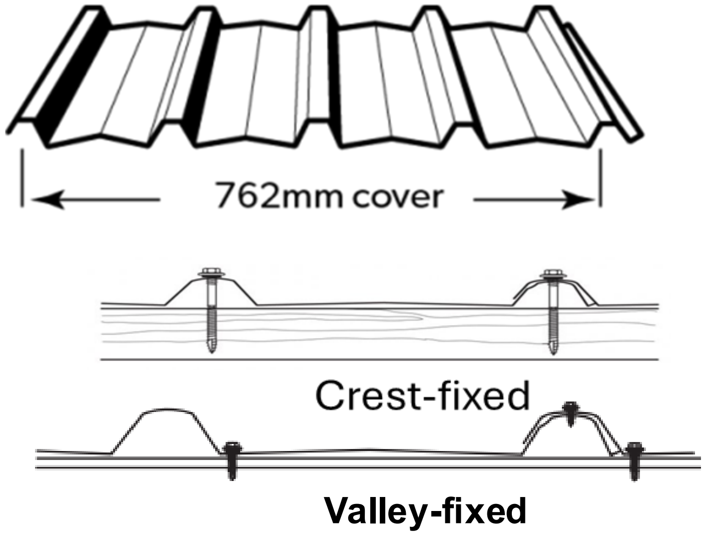
Corrugated claddings



Trapezoidal claddings with close ribs

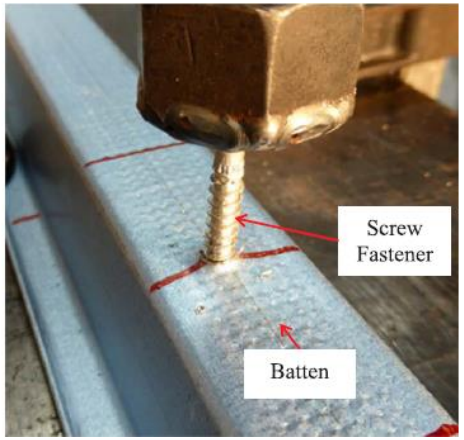


Trapezoidal claddings with wide pans

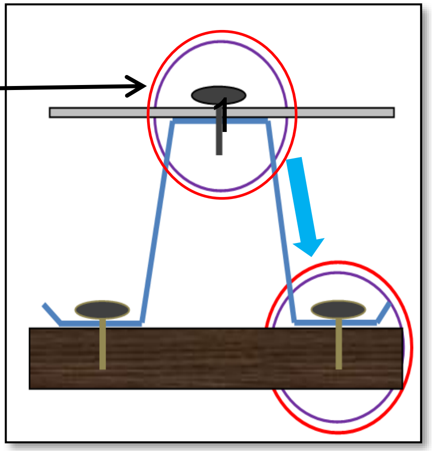


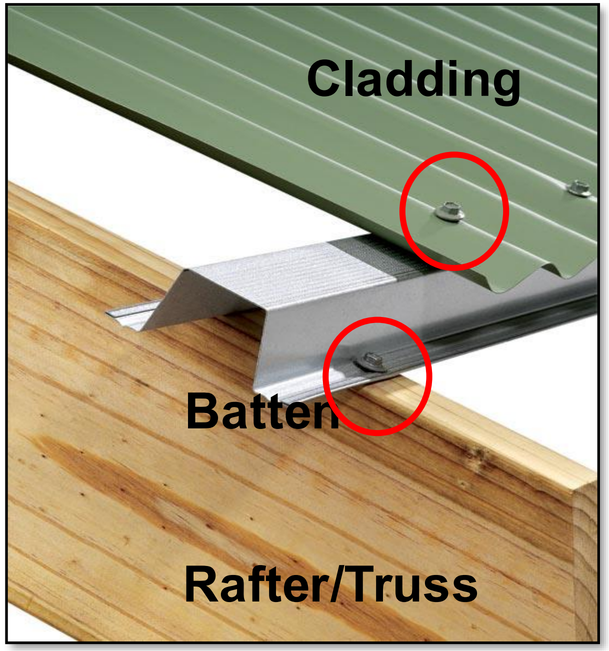
Screw Connection Failures in Steel Roof and Wall Claddings

- Two types of failures were observed: Cladding to Batten & Batten to Rafter connections – “Pull-through failures” and Cladding to Batten & Batten to Rafter connections - “Pull-out failures”

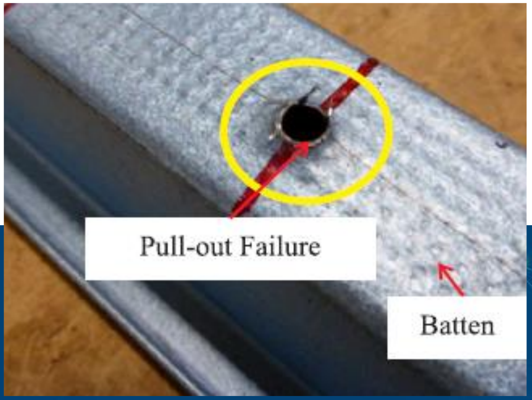


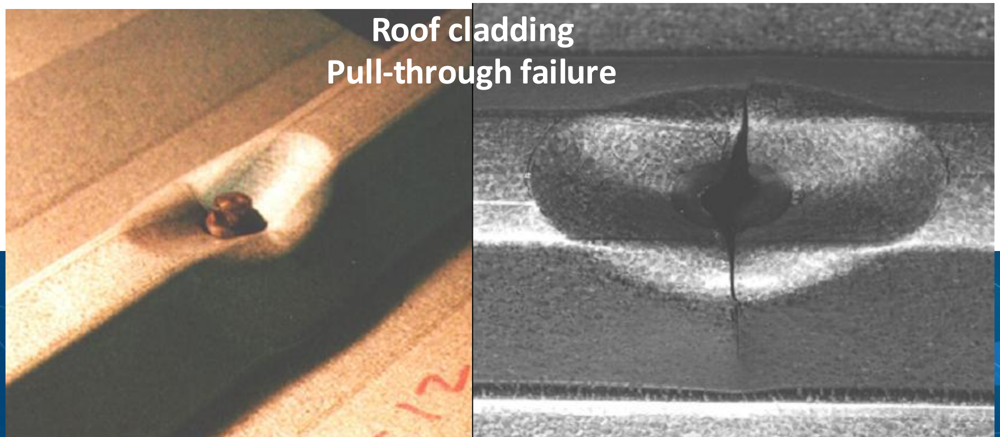
Pull-out failures

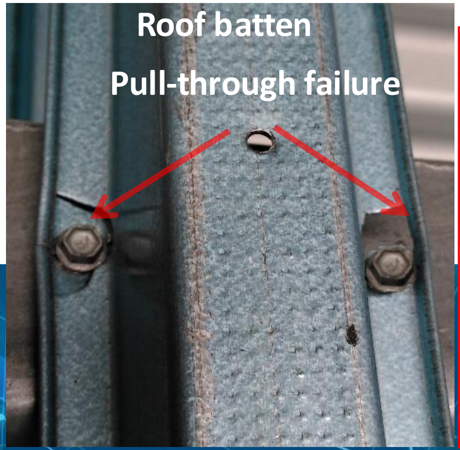




Pull-through failures







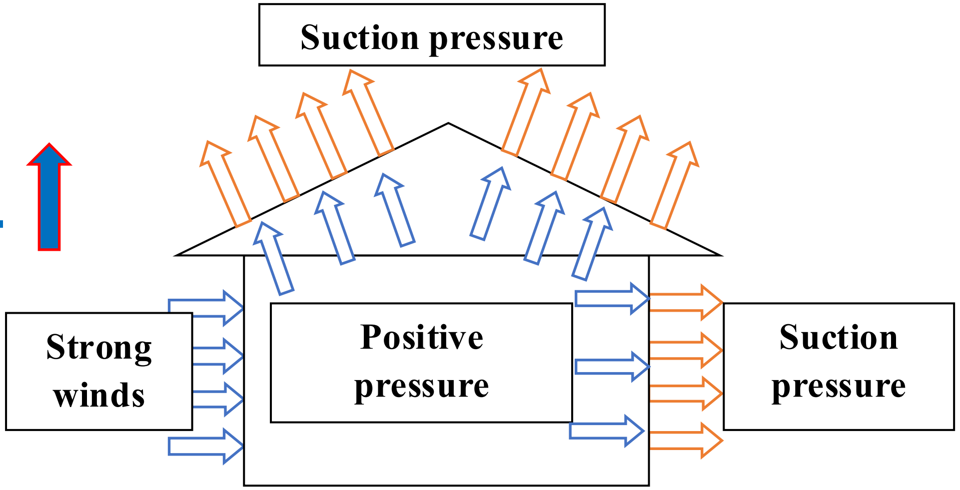
Steel Cladding Envelope Subject to Combined Wind Loading and Elevated Temperatures

- Suction pressures **+** Internal pressures

>>High wind uplift/suction loads on roof and leeward wall.

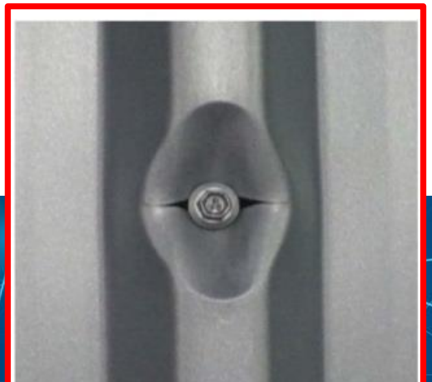
- Elevated Temperatures

>>Mechanical properties of cold-formed steel (CFS)

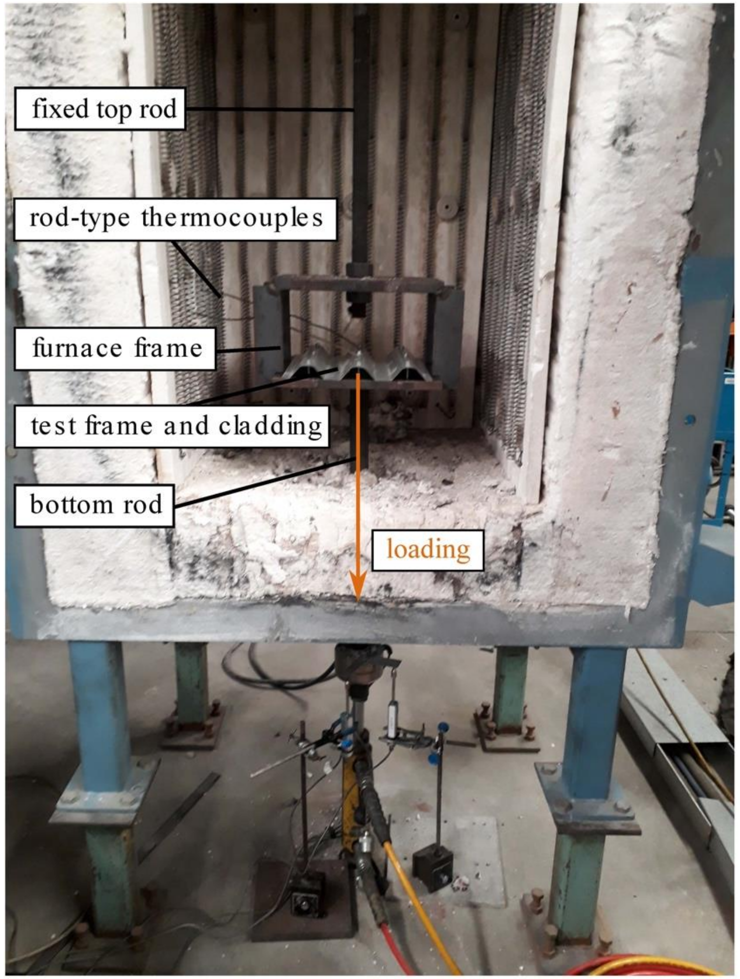


- During a bushfire, enhanced wind can further exacerbate localised failure of roof sheeting
- Transverse splitting type failure mode is particularly concerning as it can lead to ember penetration
- AS 3959 and NASH stress the importance of preventing ember ingress in bushfire-prone areas and recommend avoiding a 2 mm gap in building envelopes

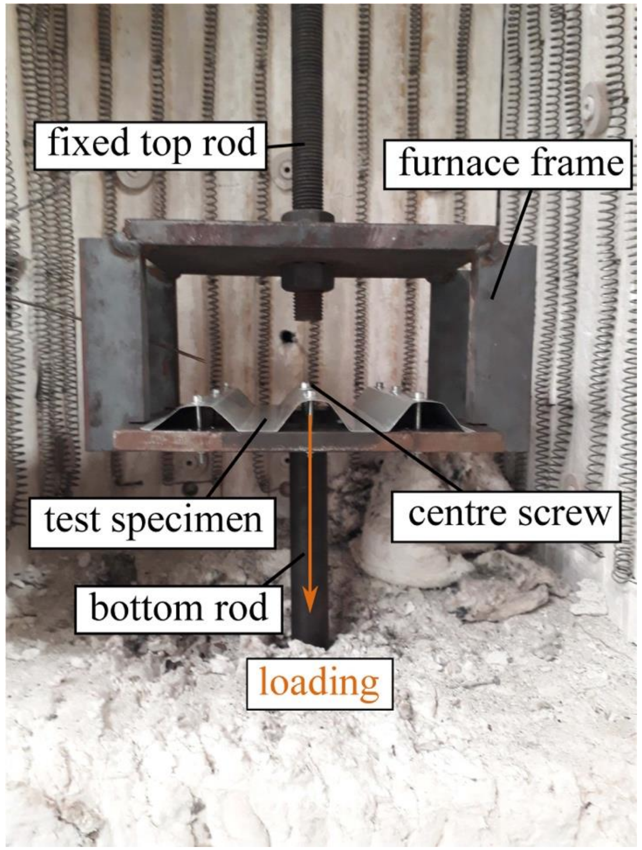
Transverse splitting

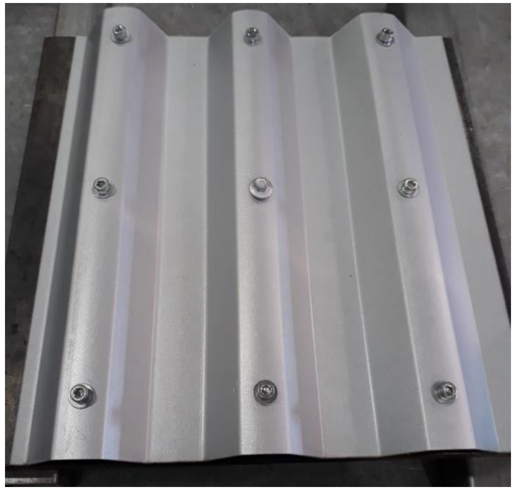


Steel Cladding Tests at Elevated Temperatures – Small Scale



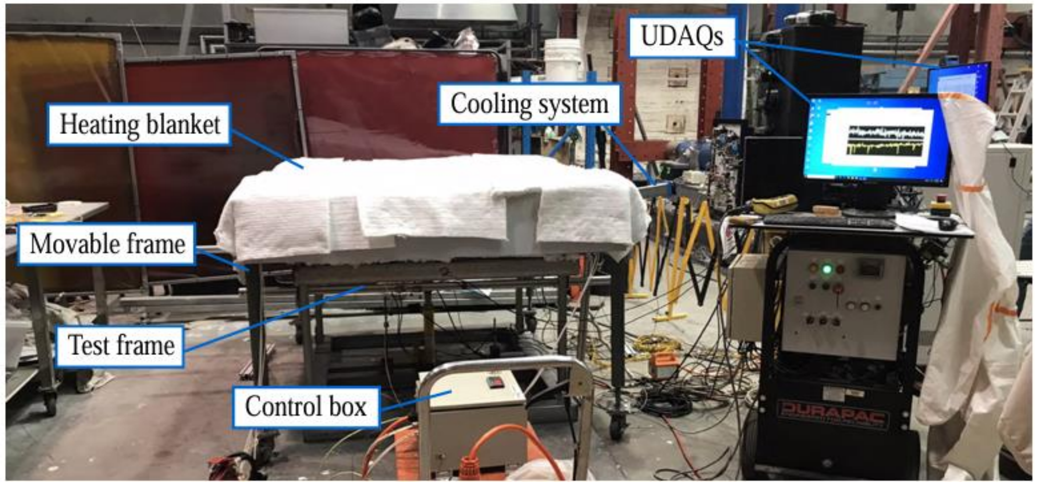
Test set-up inside an electric furnace



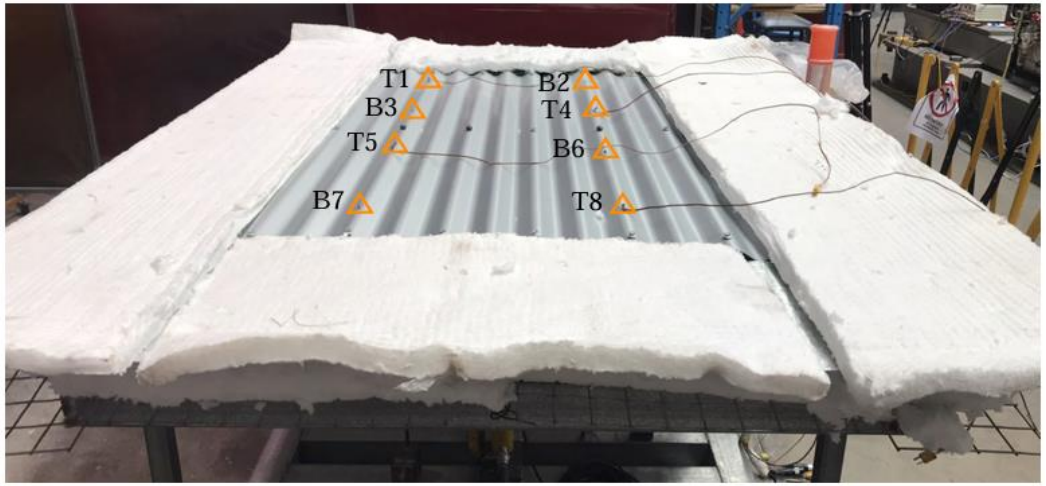


- **3 Profiles:** corrugated, trapezoidal with closer ribs and wide pans
- Based on small-scale test set-up; Specimen size: 300mmx300mm
- Centre screw fixed with two bolts to the bottom rod

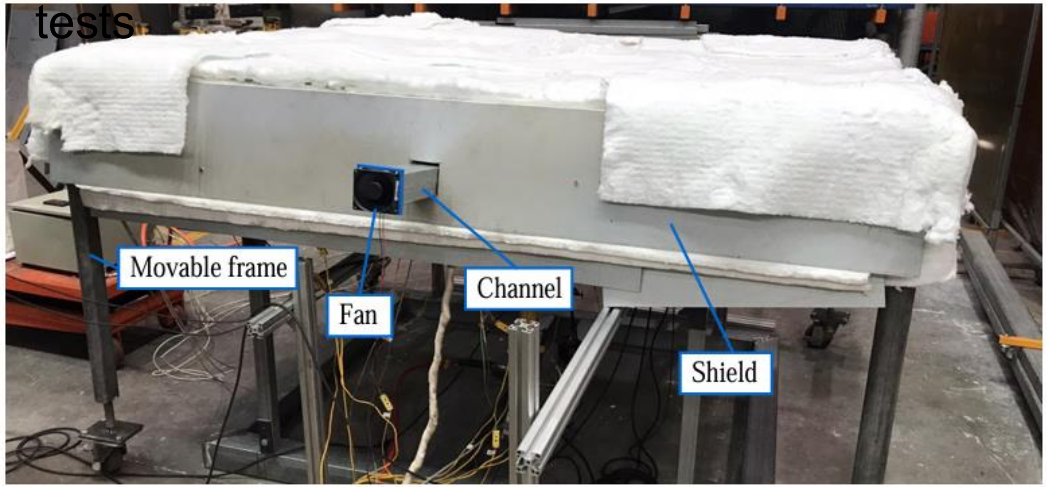
Steel Cladding Tests at Elevated Temperatures – Large Scale



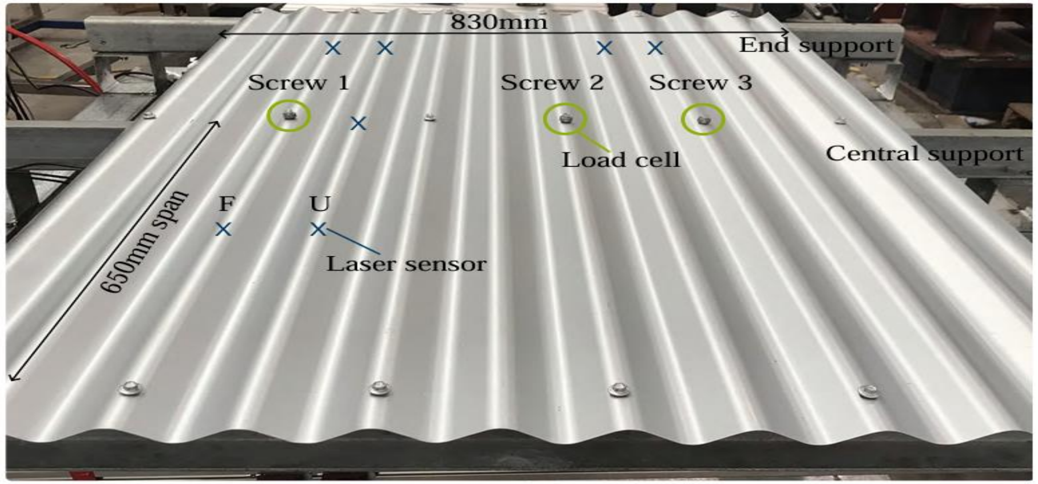
Two-span test set-up for elevated temperature tests



Locations of thermocouples



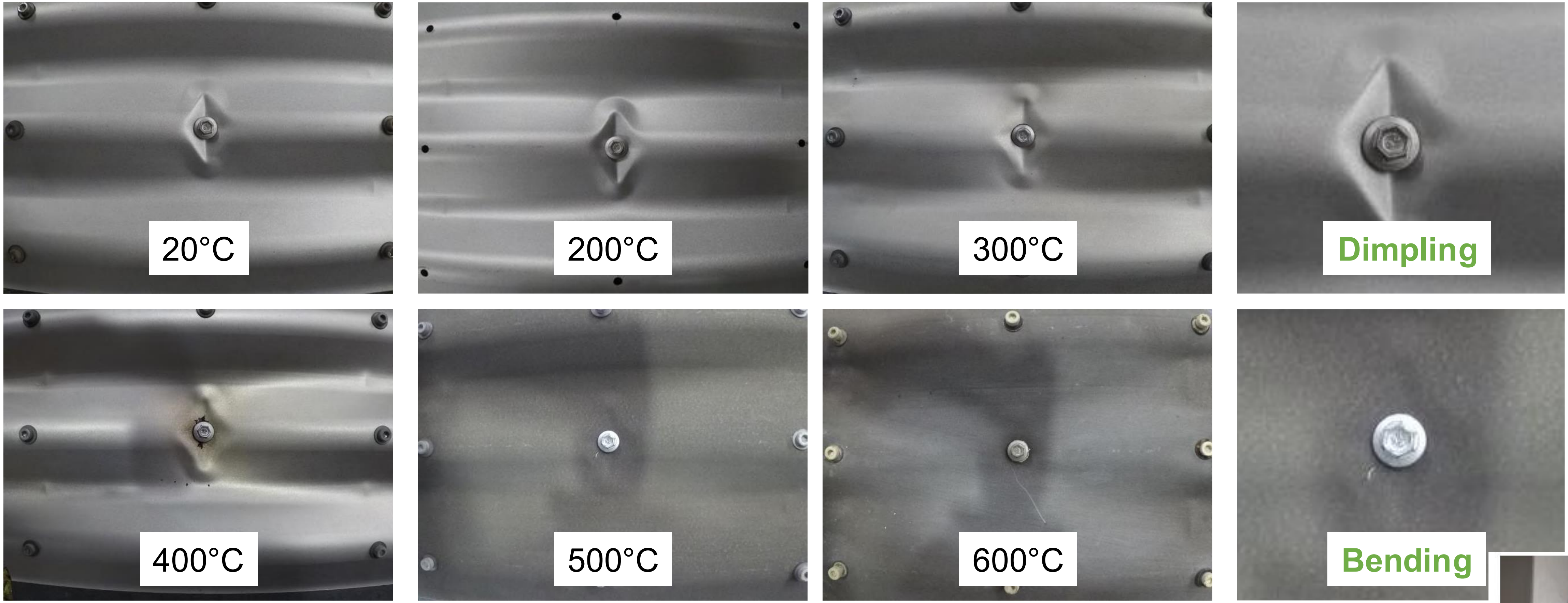
Cooling system for the load cells

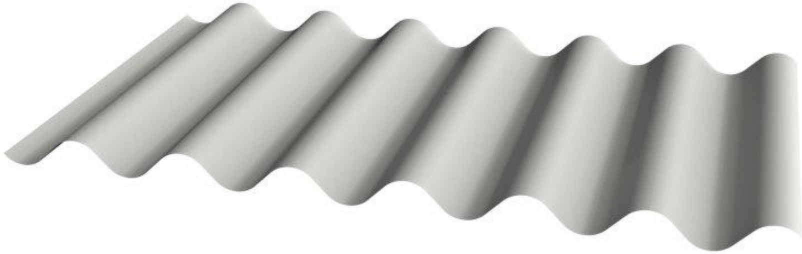


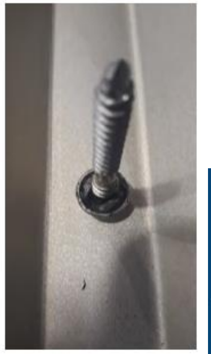
Location of laser sensors and load cells

Pull-through Failure at Elevated Temperatures

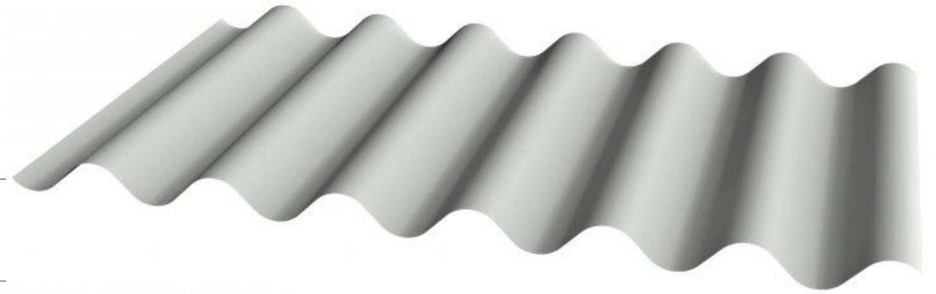
1. Corrugated CFS Cladding

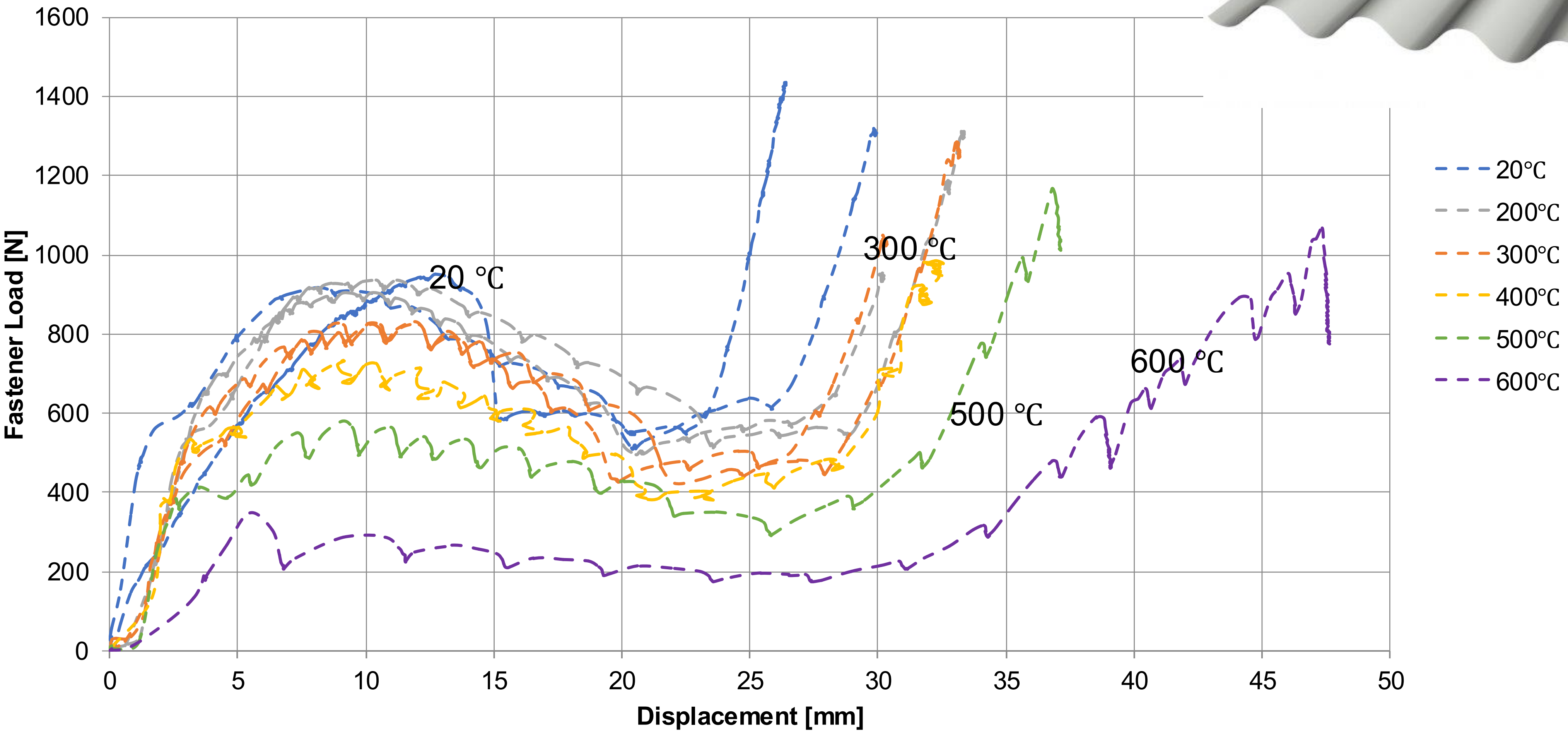




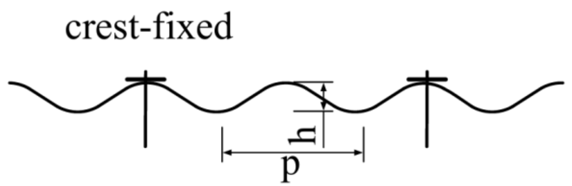


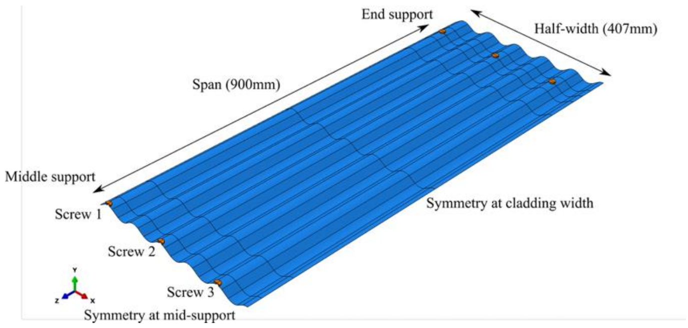
Results for 0.42 mm G550 Steel Corrugated Cladding (M6 screw)

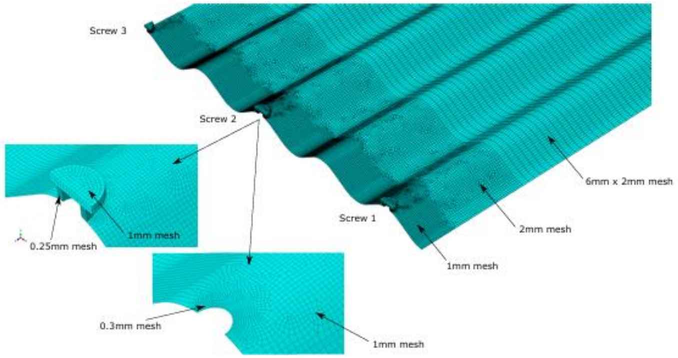


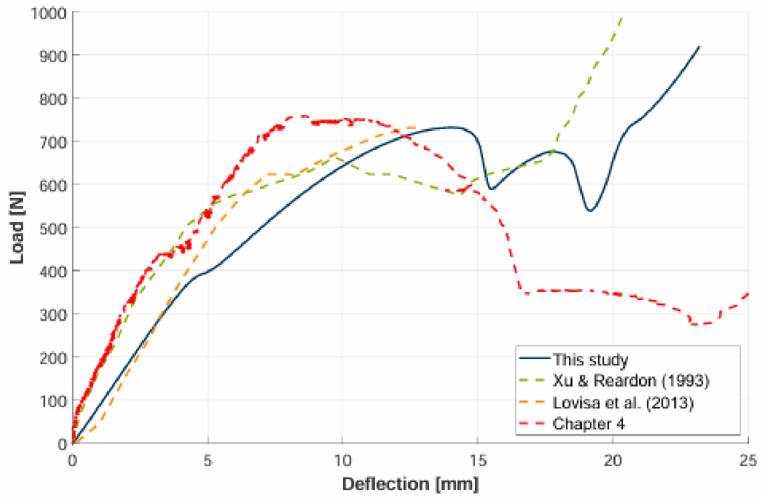


Numerical Modelling of Corrugated Cladding

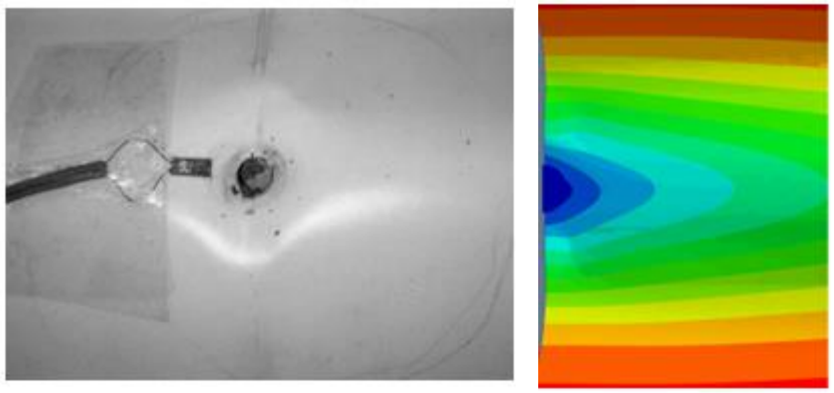




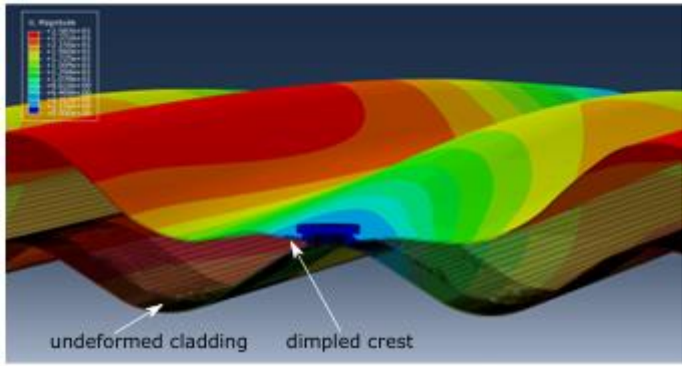




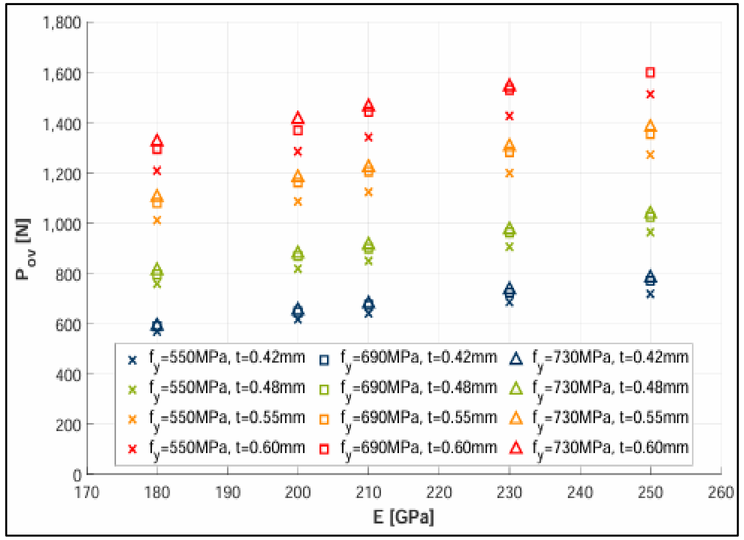
Resource	Type	P_{ov} [N]	FEA/Test
This chapter	FEA (Abaqus/CAE)	732	-
Chapter 4	Test (Small-scale)	727	1.01
Lovisa (2015)	Test (Small-scale)	619	1.18
Lovisa et al. (2013)	Test (Large-scale)	681	1.07
Mahendran (1995*b*)	Test (Small-scale)	670	1.09
Mahendran (1994*a*)	Test (Large-scale)	870	0.84
Xu and Reardon (1993)	Test (Large-scale)	663	1.10
	Mean	709	1.05
	COV	0.106	0.101

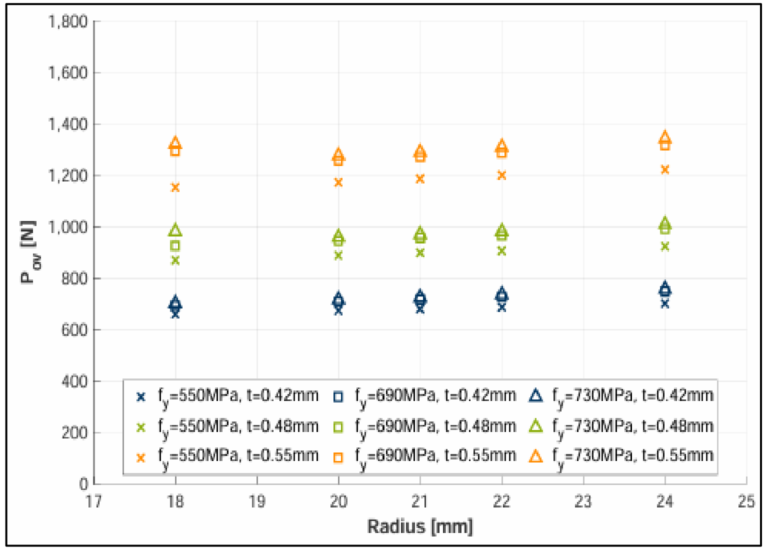


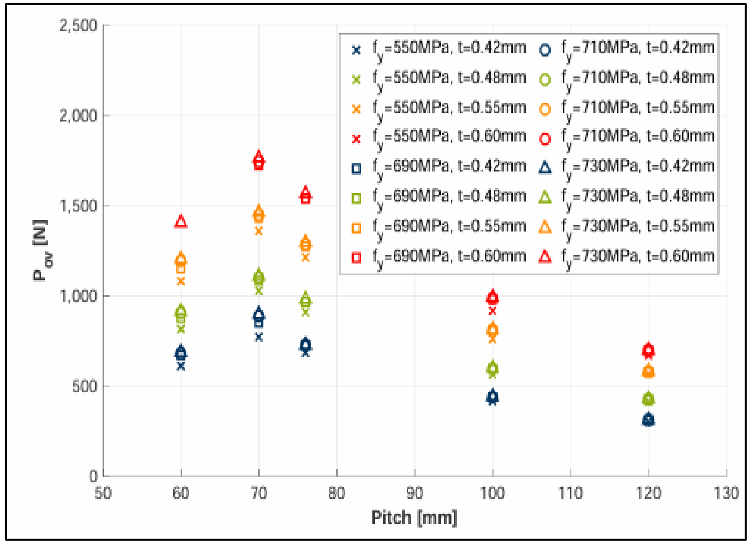
Dimpling type failure

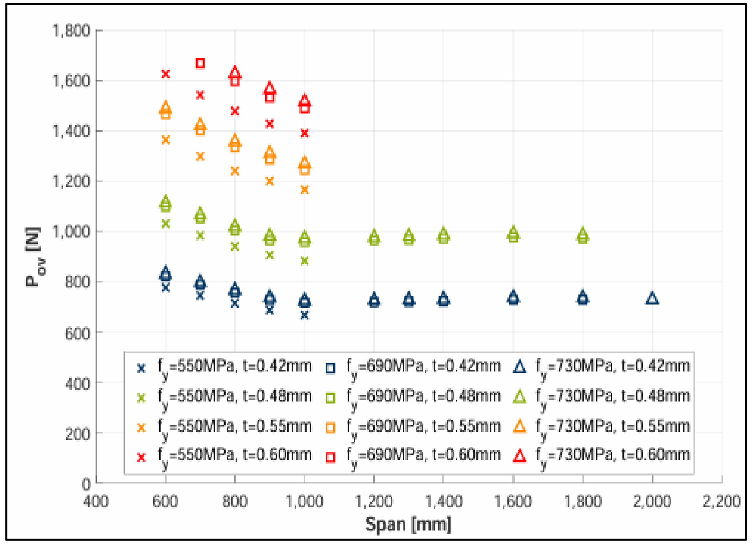


Influence of Parameters on Pull-through Capacity









Pull-through capacity equation

$$P_{ov} = 0.1 g \lambda E^{0.7} f_y^{0.3} t^2$$

g = geometry parameter
λ = span parameter

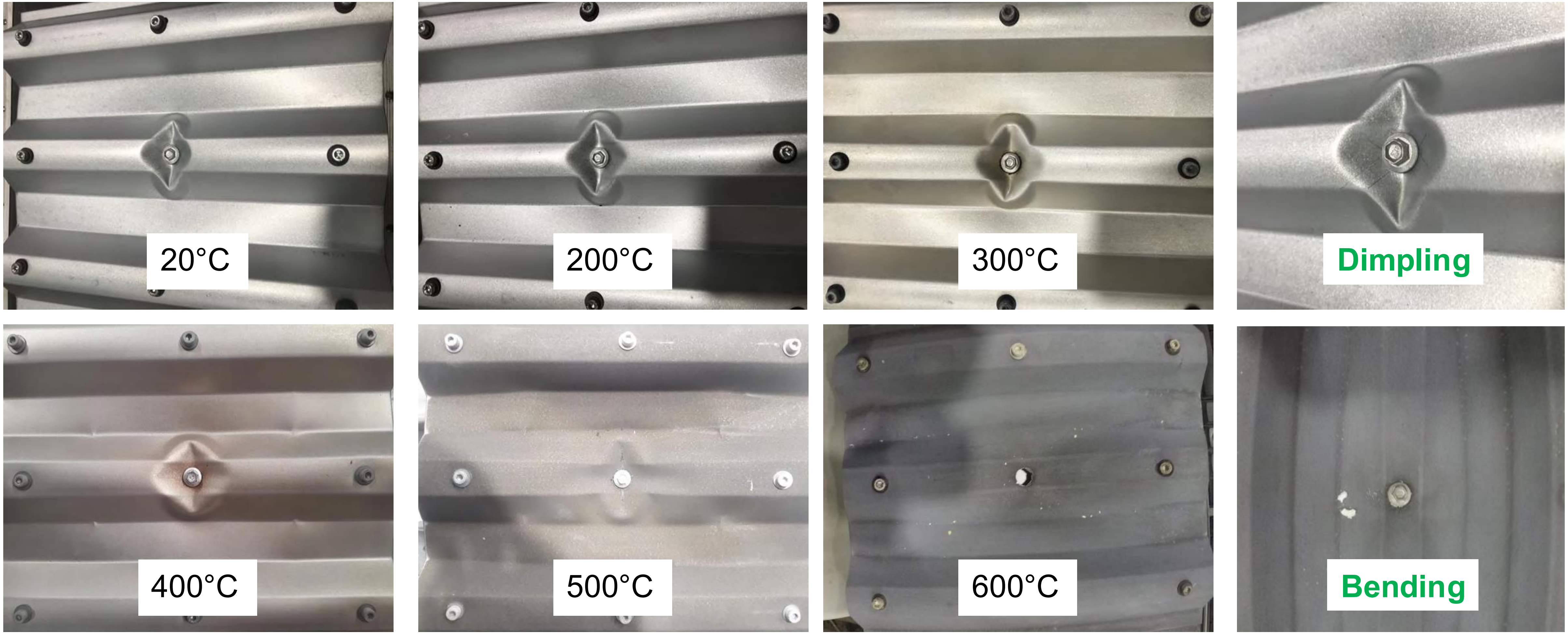
$$g = 14.5\left(\frac{h^{0.8} r^{0.2}}{p}\right)^2 + 1.2\left(\frac{h^{0.8} r^{0.2}}{p}\right) - 0.05$$

$$\lambda = 5.7\left(\frac{s}{t}\right)^{-0.22} \; for \; {}^{s}/_{t} \leq 2000$$

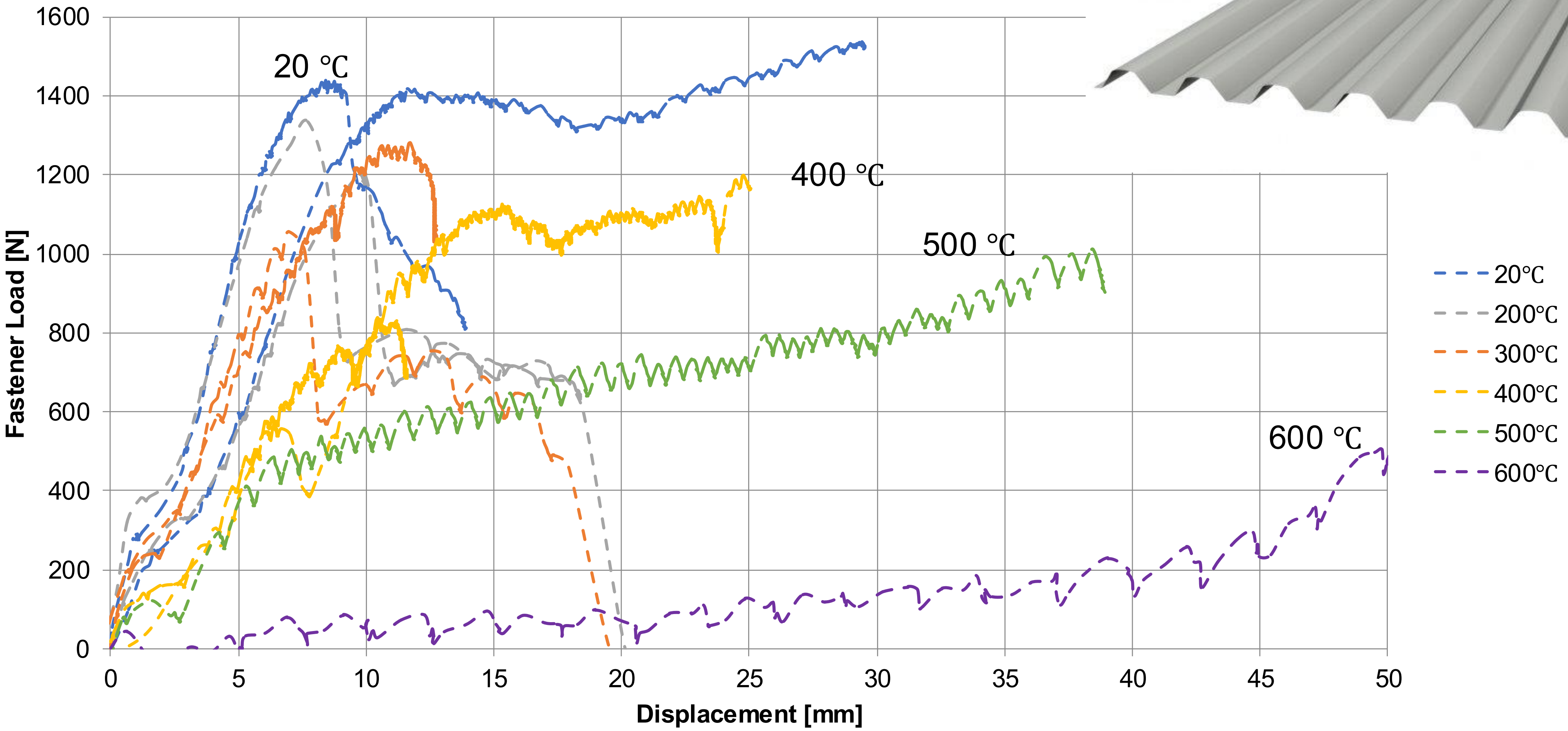
$$\lambda = 1.07 \; for \; {}^{s}/_{t} > 2000$$

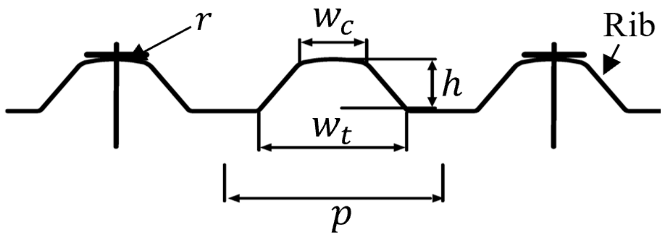
$* \; Note \; s = Span$

2. Trapezoidal CFS Cladding with Closely Spaced Ribs

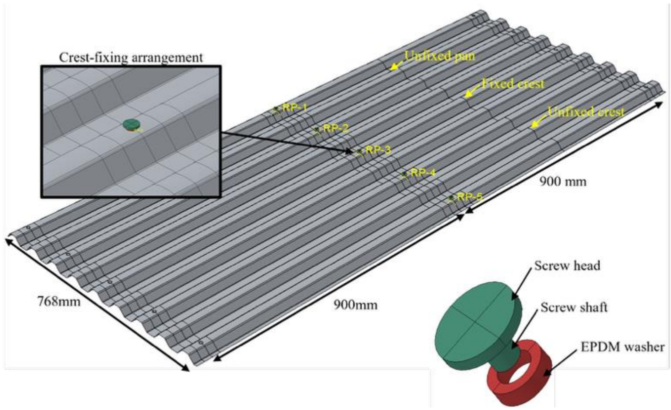


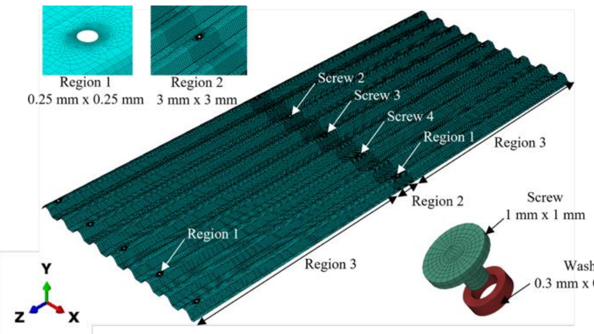
Results for 0.42 mm G550 Steel Trapezoidal Cladding with Close Ribs (M6 screw)

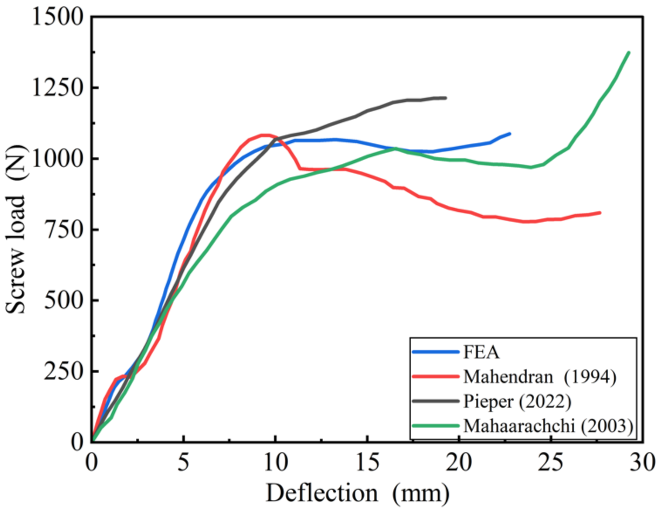




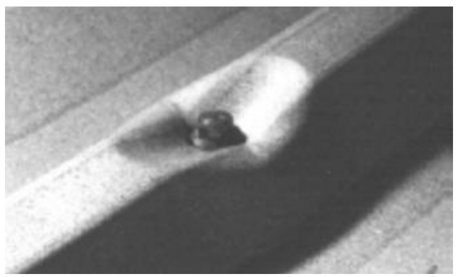
ds – screw head diameter

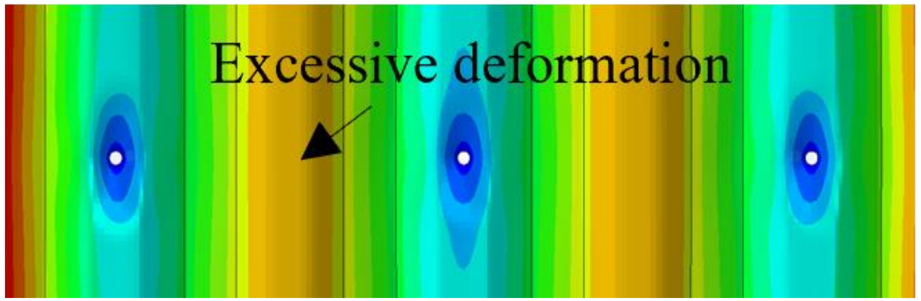


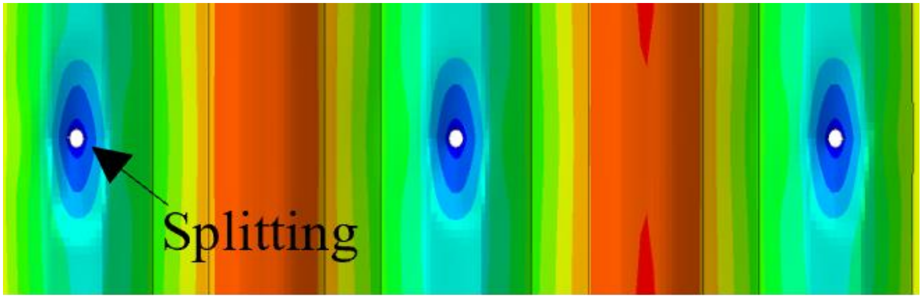


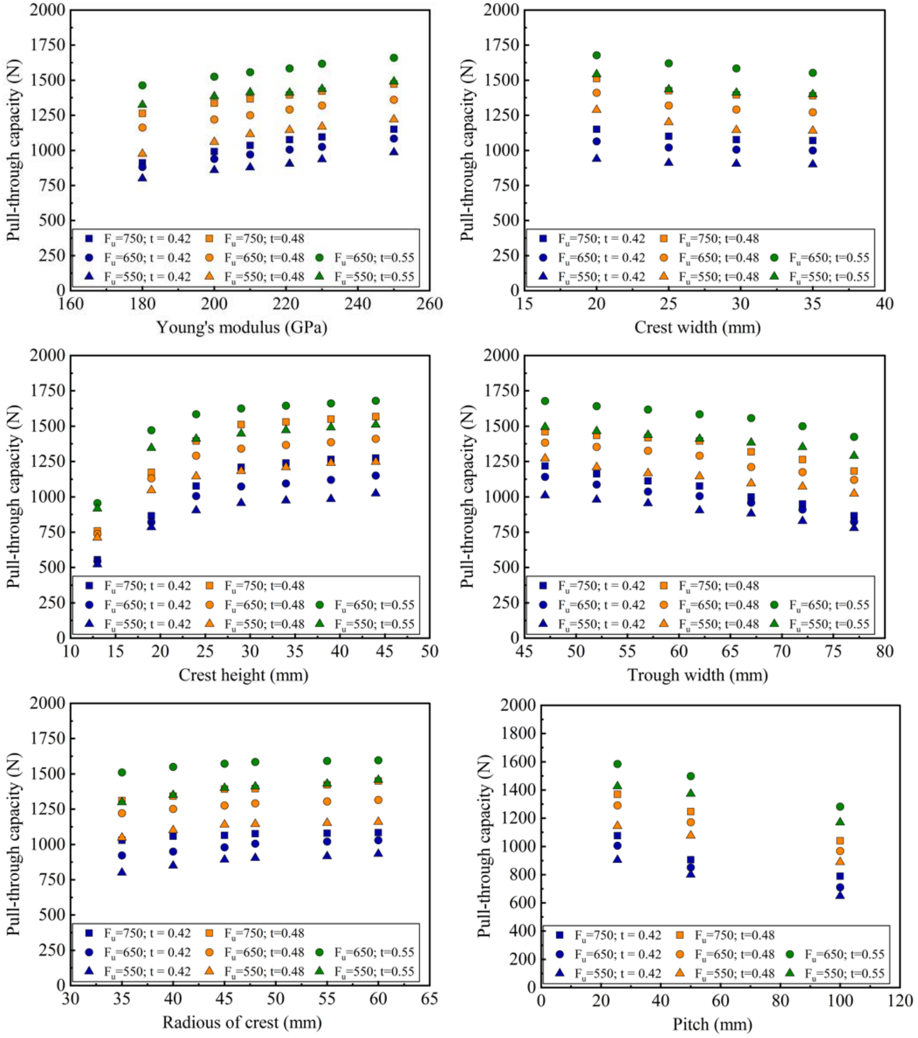


Source	Test type	P_{ov} (N)	FEA/Test
FE analysis (FEA)		1060	
Pieper (2022)	Test (Small-scale)	1098	0.96
Mahaarachchi (2003)	Test (Large-scale)	1063	0.99
Mahendran (1995)	Test (Small-scale)	1280	0.82
Mahendran (1994)	Test (Large-scale)	1210	0.87
Xu and Reardon (1993)	Test (Large-scale)	1257	0.84
	Mean	1161	0.90
	COV	96	0.07
	Corrected Mean	1073	0.98
	Corrected COV	21	0.02

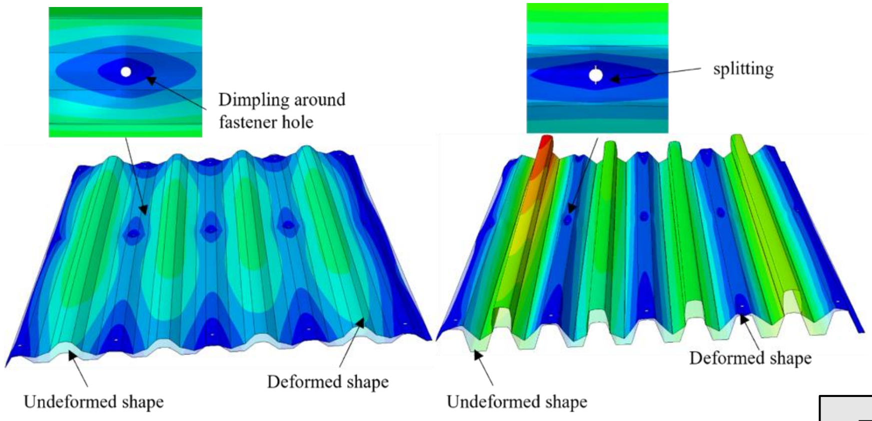






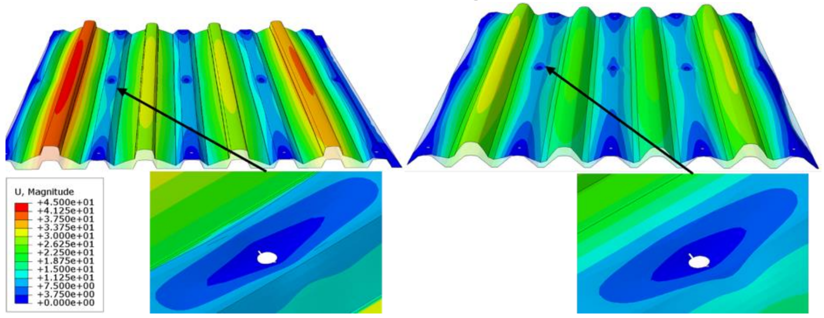


Effect of crest height

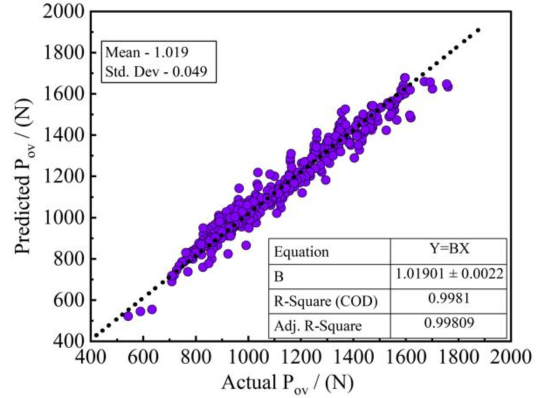


h=13 mm h=44 mm

Effect of trough width



w_t=47 mm w_t=77 mm



Equation	Y=BX
B	1.01901 ± 0.0022
R-Square (COD)	0.9981
Adj. R-Square	0.99809

Pull-through capacity equation

$$P_{ov} = 0.51 g_1 g_2 \lambda (E f_u)^{0.5} t^2$$

$g_1 and\ g_2$ = geometry parameters
λ = span parameter

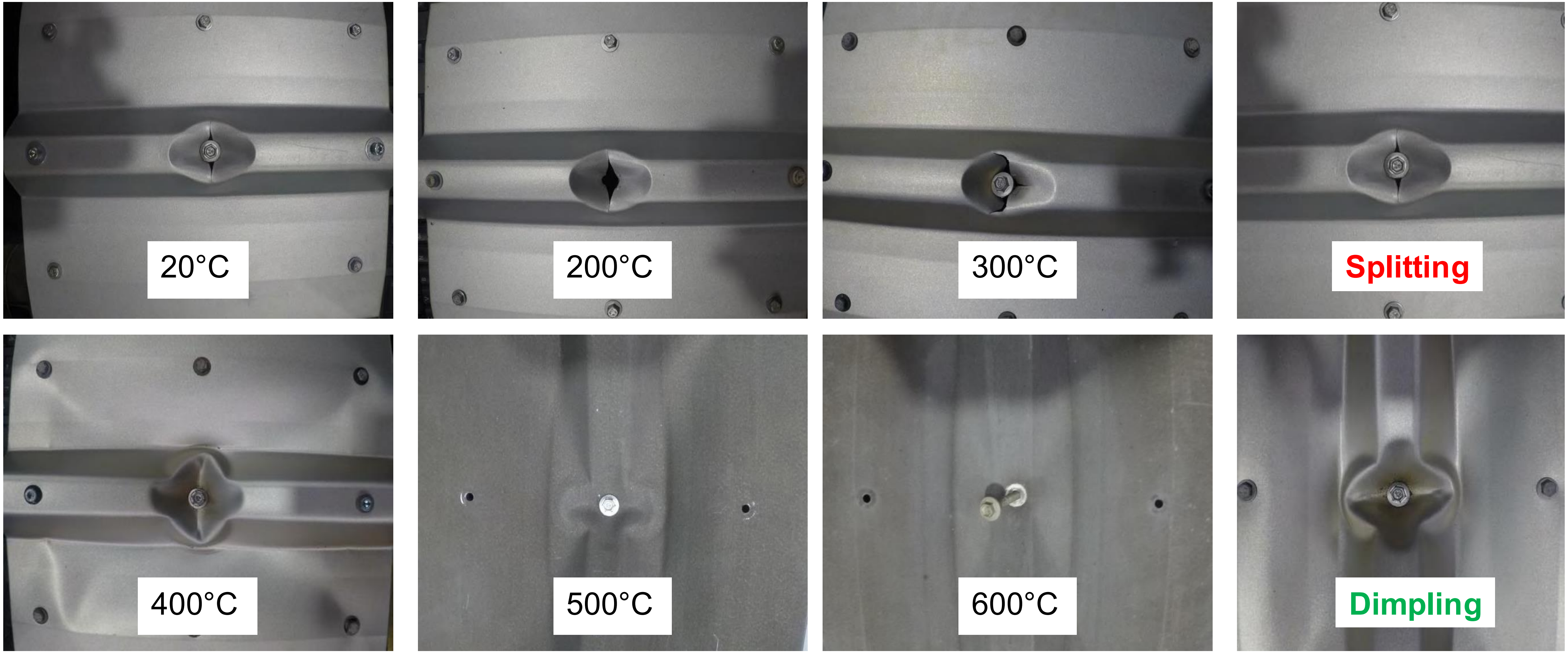
$$g_1 = -5.3((h^{0.9} r^{0.1})/p)^2 + 4.53((h^{0.9} r^{0.1})/p) + 0.015$$

$$g_2 = -2((w_t^{0.2} w_c^{0.2})/(h^{0.2} d_s^{0.2}))^2 + 5.2((w_t^{0.2} w_c^{0.2})/(h^{0.2} d_s^{0.2})) - 2.27$$

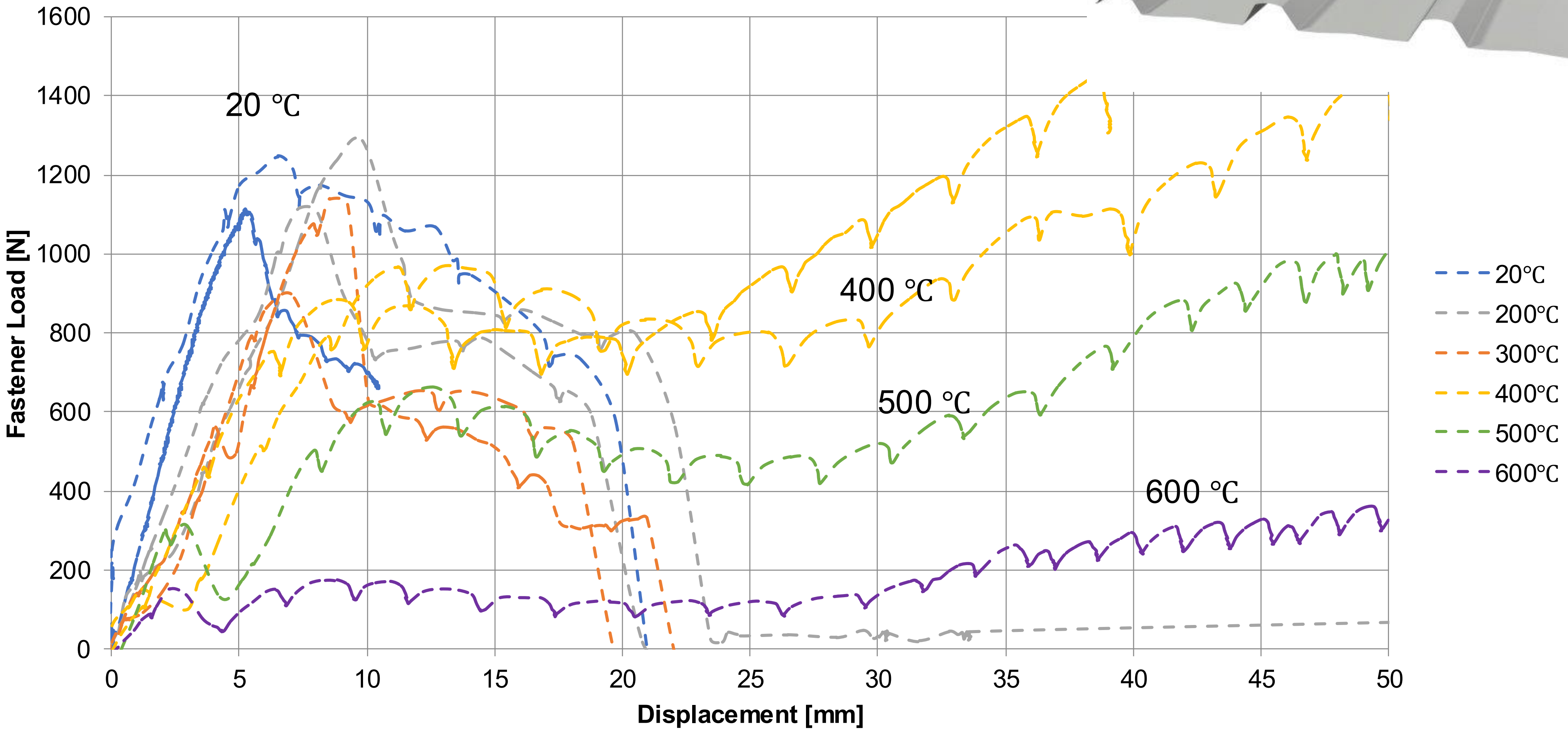
$$\lambda = 1.98(l/d_s)^{-0.2}$$

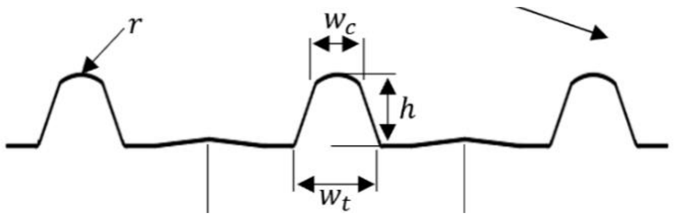
$*$ Note $l = Span$

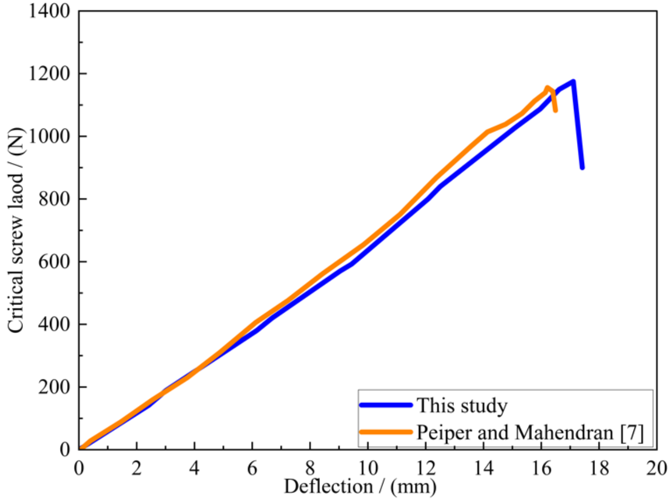
3. Trapezoidal CFS Cladding with Wide Pans

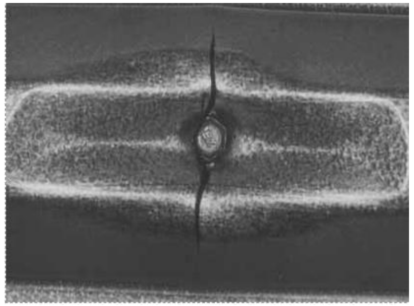


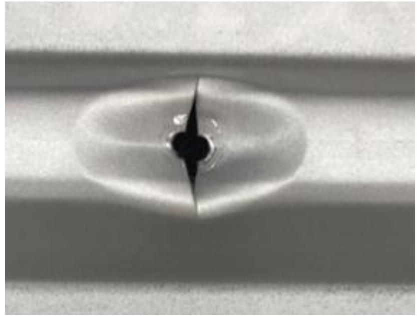
Results for 0.42 mm G550 Steel Trapezoidal Cladding with Wide Pans (M6 screw)

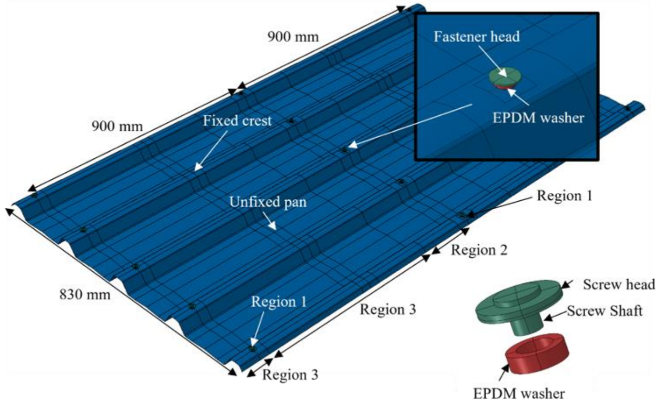




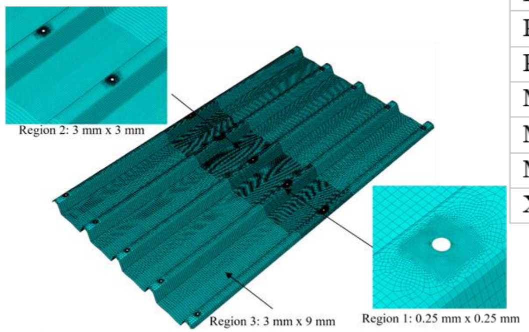


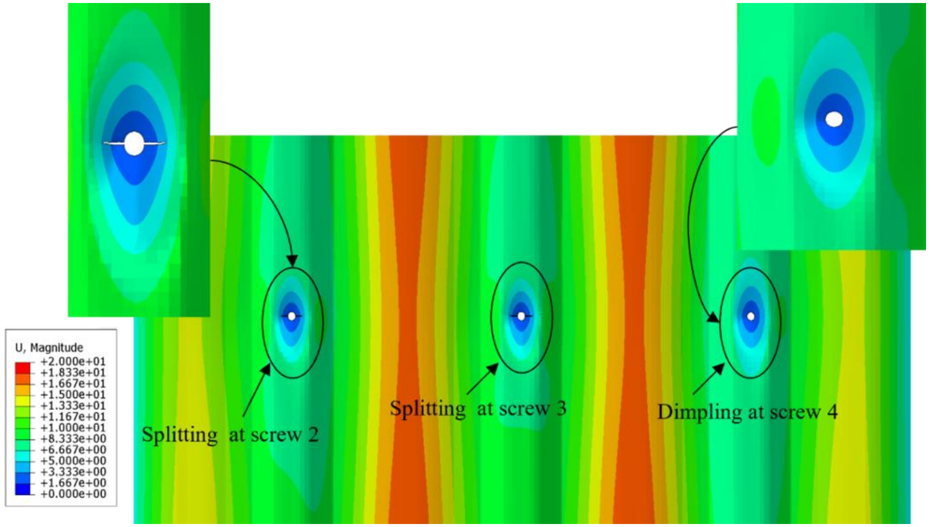




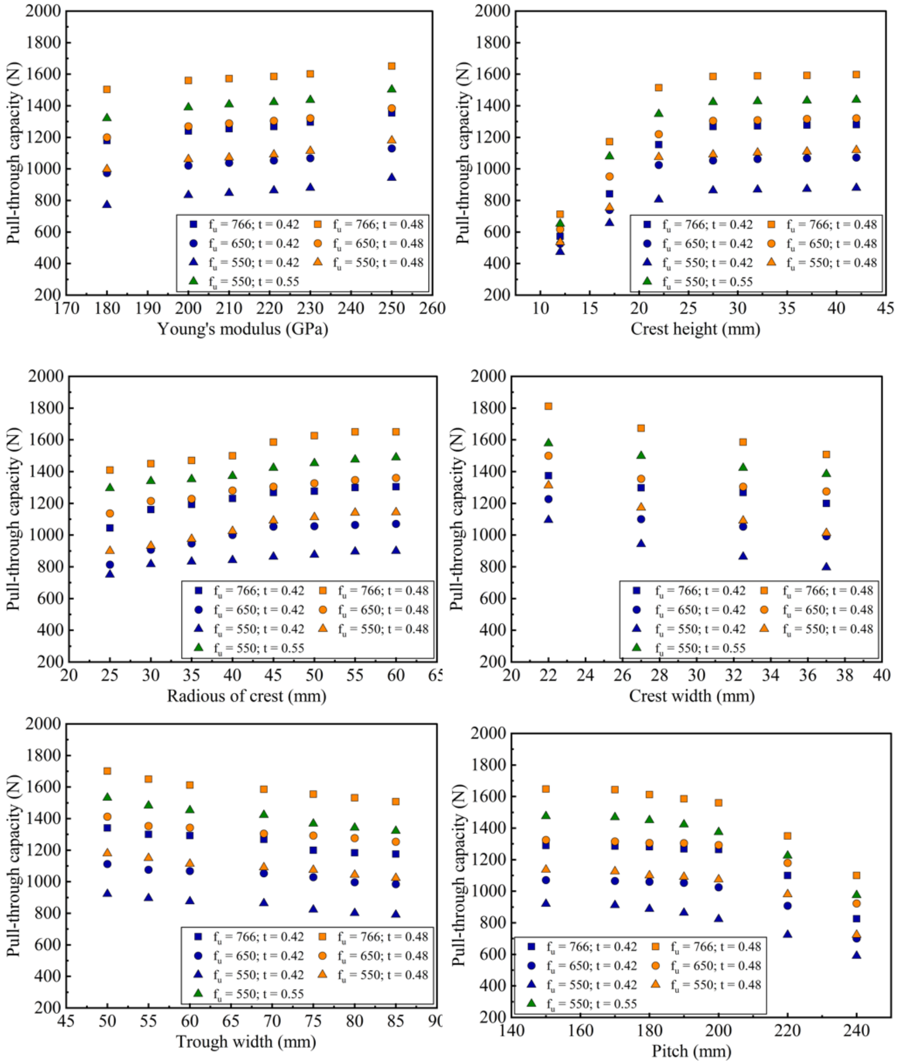


Literature	Test type	P_{ov} (N)	$P_{ov(FE)}/P_{ov(Test)}$
FE model		1185*	-
Pieper and Mahendran [7]	Large-scale (Line load)	1156*	1.03
Pieper and Mahendran [10]	Small-scale	1180*	1.00
Mahaarachchi and Mahendran [13]	Large-scale (Pressure load)	1180*	1.00
Mahendran [25]	Small-scale	1250**	0.95
Mahendran [9]	Large-scale (Pressure load)	1430**	0.83
Xu and Reardon [6]	Large-scale (Mid-span load)	1350**	0.88
	Mean		0.95
	COV		0.07

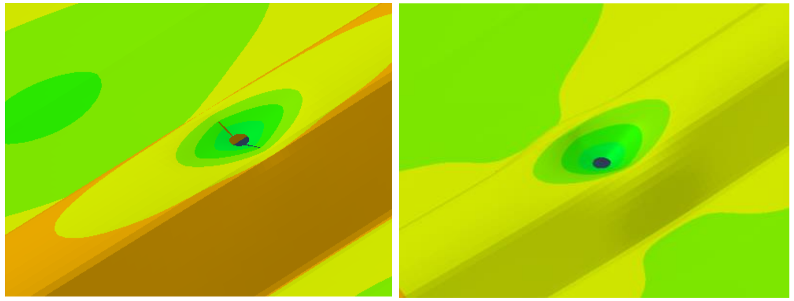




CRICOS No.00213J

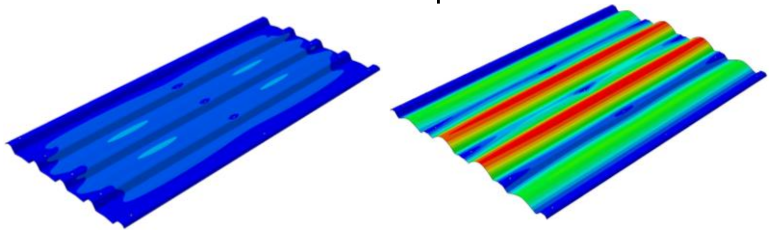


Effect of crest height

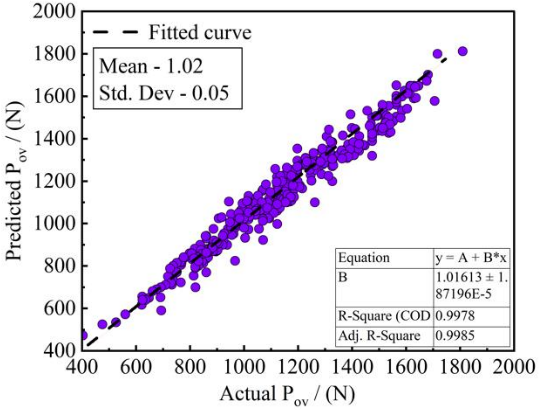


h=42 mm h=17 mm

Effect of pitch



p=150 mm p=240 mm



Pull-through capacity equation

$$P_{ov} = 1.14[7.6 g_1 g_2 \lambda f_u t^2]$$

g_1 *and* g_2 = geometry parameters
λ = span parameter

$$g_1 = -56.8((h^{0.65} r^{0.35})/p)^2 + 22.9((h^{0.65} r^{0.35})/p) - 1.25$$

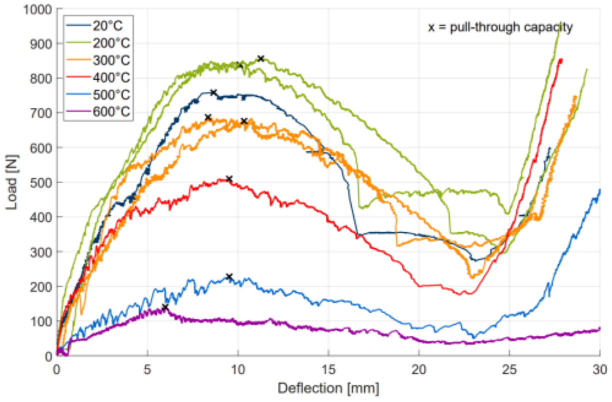
$$g_2 = 1.9\left(\left(w_t^{0.25} w_c^{0.15}\right)/d_s^{0.4}\right)^{-1.5}$$

$$\lambda = 3.4(l/d_s)^{-0.32}$$

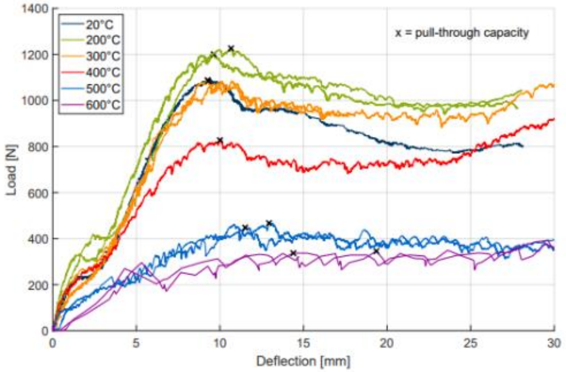
$*$ Note $l = Span$

CRICOS No.00213J

Pull-through Capacity of Crest-fixed CFS Claddings at Elevated Temperatures



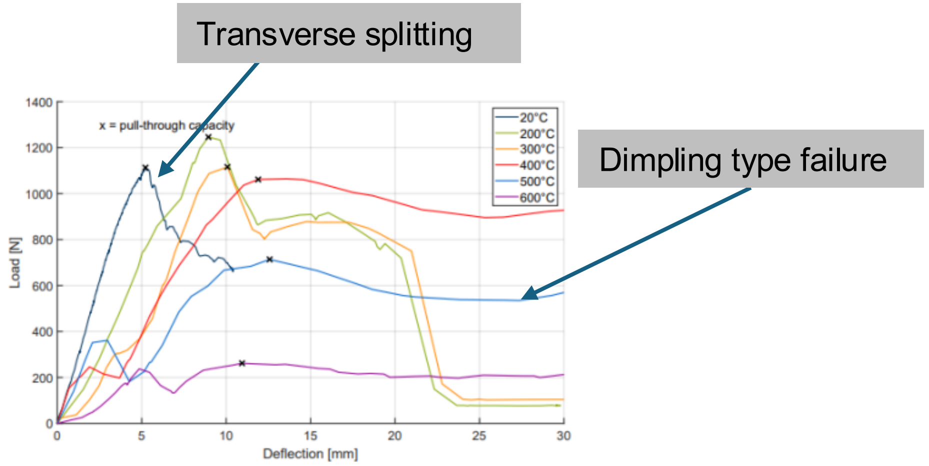
Corrugated cladding



Trapezoidal cladding with close ribs

Temperature (⁰C)	Pull-through failure load (N) – per fastener		
	Crest-fixed		
	Corrugated	Trapezoidal	
		Closely spaced ribs	wide pans
20	737	1081	1180
200	847	1213	1266
300	681	1076	1127
400	509	920	1105
500	228	457	714
600	140	341	262

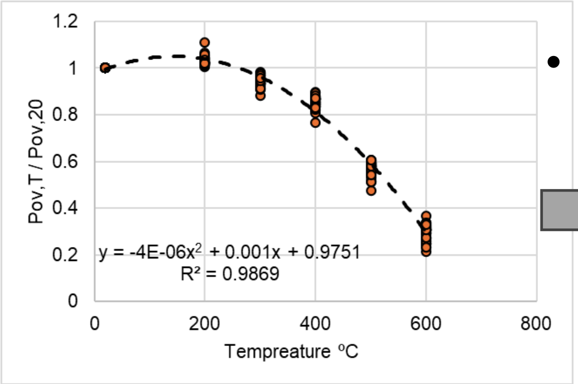
About 50% reduction in pull through capacity compared to ambient condition



Trapezoidal cladding with wide pans

Crest-fixed Claddings at Elevated Temperatures

Trapezoidal cladding with closely spaced ribs



- $\frac{P_{ov,T}}{P_{ov,20}}$ = Reduction factor at elevated temperature

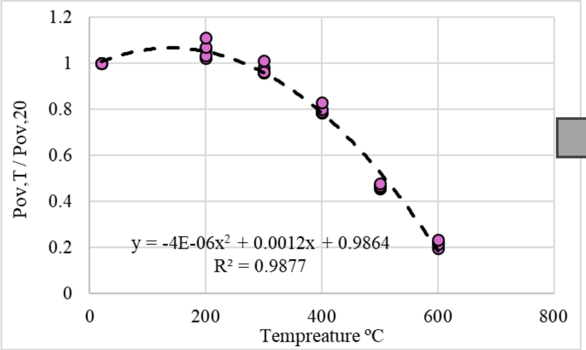
$$\frac{P_{ov,T}}{P_{ov,20}} = -4 \times 10^{-6} T^2 + 0.001T + 0.9751$$

Corrugated cladding

$$\frac{P_{ov,T}}{P_{ov,20}} = aT + b$$

T (°C)	$a(10^{-3})$	b
T<400	-0.709	1.02
400<T<600	-2.468	1.72

Trapezoidal cladding with wide pans



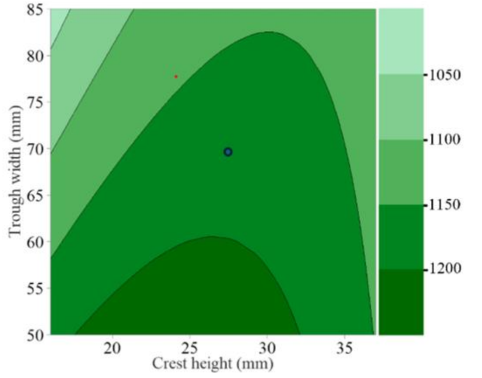
$$\frac{P_{ov,T}}{P_{ov,20}} = -4 \times 10^{-6} T^2 + 0.0012T + 0.9864$$

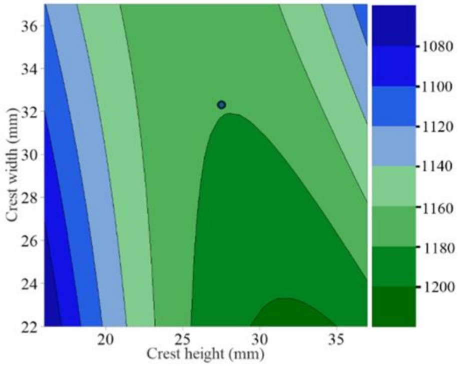
$$P_{ov} = 0.51 g_1 g_2 \lambda (E f_u)^{0.5} t^2$$

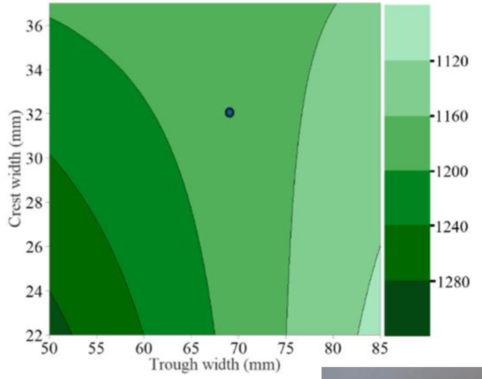
Bushfire-resilient Cladding Design

According to **AS 3959 and NASH**:

- **BAL-40 and BAL-FZ zones** require special roof design measures to **prevent ember penetration**.
- However, even in **lower BAL levels**, openings created by **splitting failures can allow ember entry into roof spaces**, increasing ignition risk.

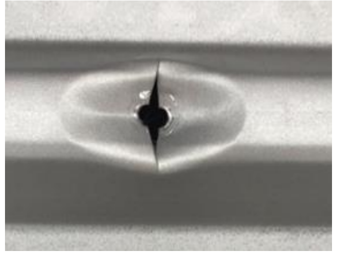






● - Current profile

Instead of only increasing strength, we used the interaction plots to identify a geometry that controls the failure mode: promoting dimpling while avoiding splitting.



Design Region Identified

- From the interaction plots, a **geometric region that avoids splitting failure** can be identified while maintaining adequate capacity (within 10%).
  - Crest height: 22 to 27 mm
  - Crest width: 25 to 30 mm
  - Trough Width: 62 to 75 mm

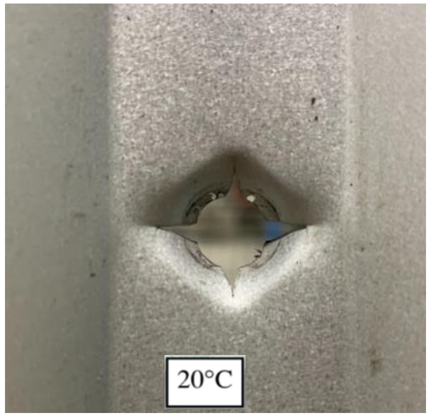
Current profile

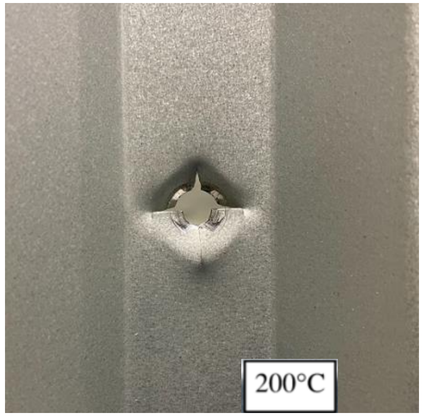
Crest height *28 mm*, $w_c = 32.5\ mm$

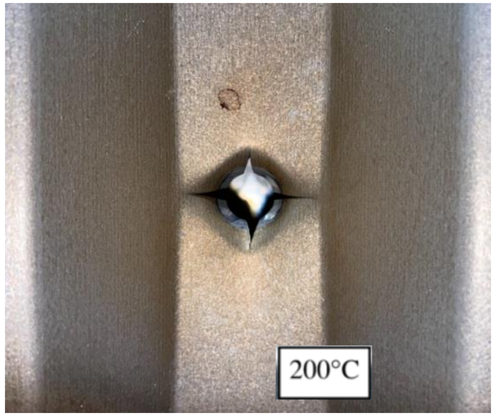
$w_t = 69\ mm$

Valley-fixed Steel Claddings

- Failures are always due to splitting caused pull-through failures at ambient and elevated temperatures – no localised dimpling type
- Two to three times higher pull-through capacities than crest-fixed steel claddings
- Pull-through capacity sustained was more than **60%** compared to the ambient condition
- Valley-fixed cladding maintains relatively better performance at higher temperatures

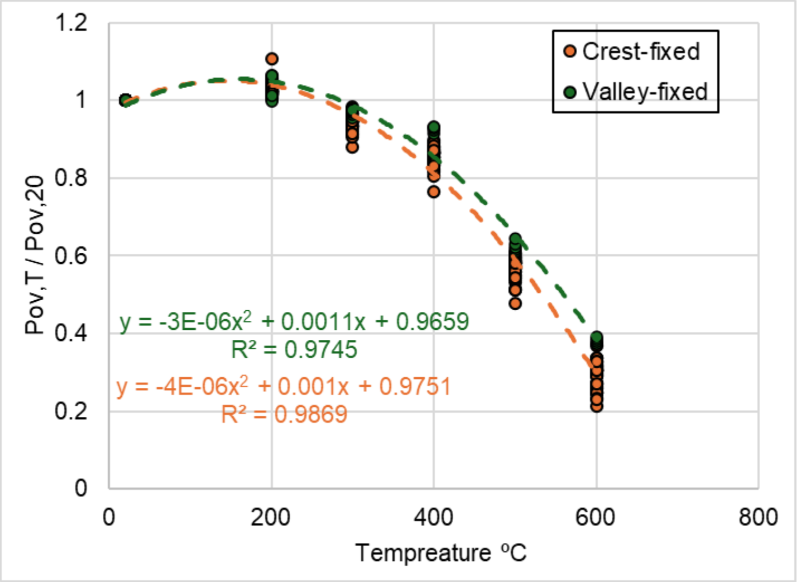




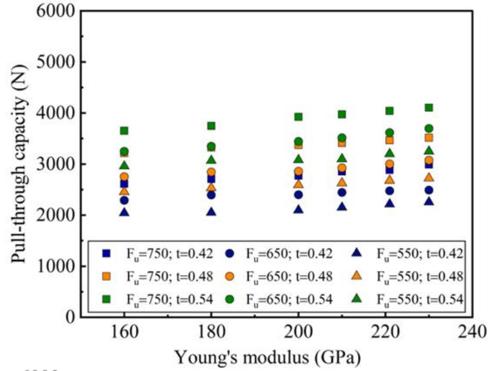


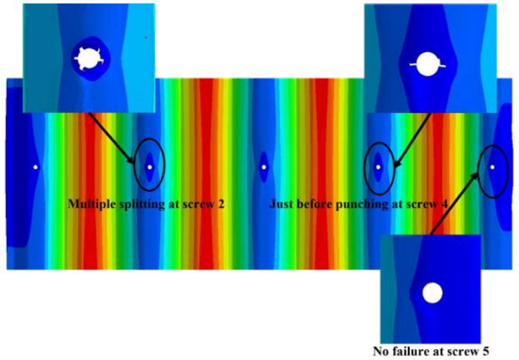
Pull-through Failure Load (N)

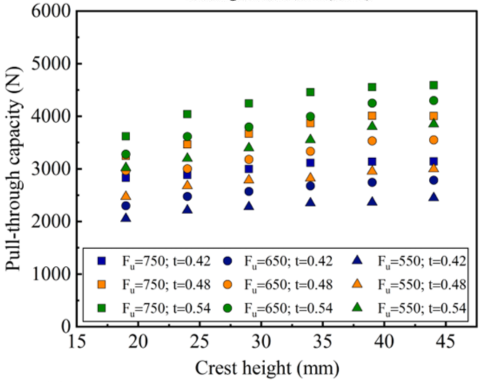
Temperature (^{0}C)	Corrugated	Trapezoidal
20	2826	1854
200	2848	2014
300	2739	2772
400	2624	2919
500	1762	2033
600	971	1130

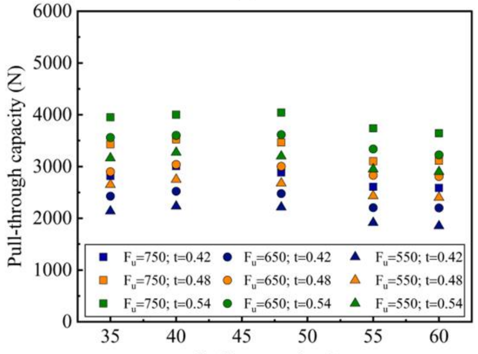


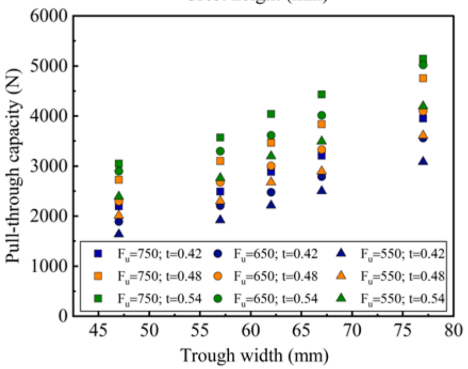
Results for G550 Valley-fixed Trapezoidal Cladding with Close Ribs

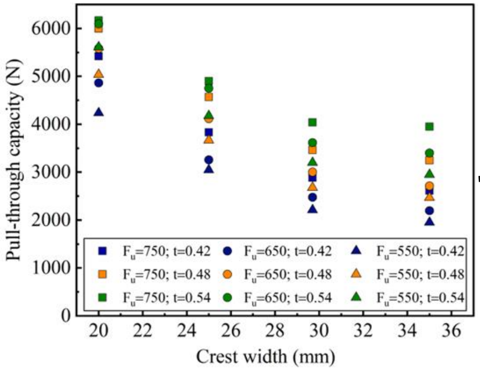


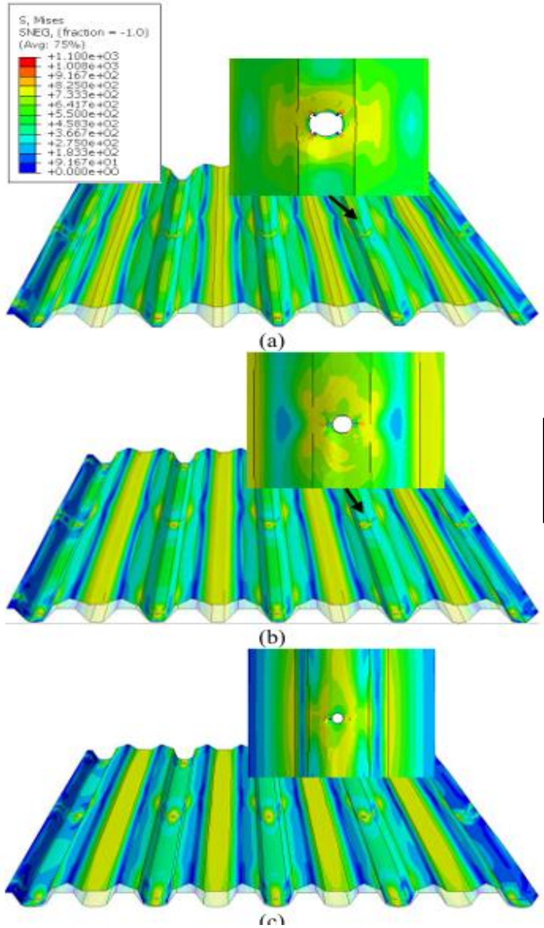












Pull-through capacity equation

$$P_{ov} = 0.87\left[6 g_1 g_2 \lambda {f_u}^{0.8} E^{0.2} t^2\right]$$

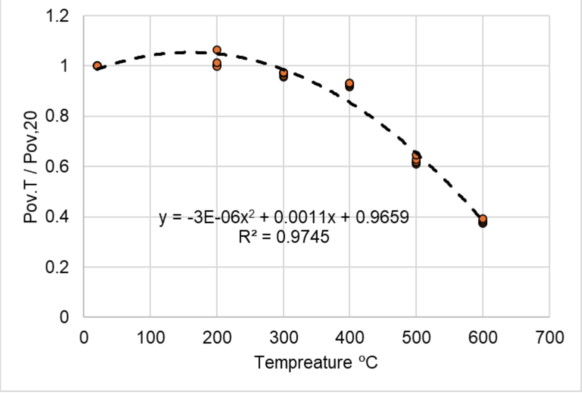
$$g_2 = 1.52(h/p)^{0.27}$$

$$g_1 = 0.45(w_t/w_c)^{1.22}$$

$$\lambda = 14.75(l/d_s)^{-0.7}$$

$g_1 \, and \, g_2$ = geometry parameters
λ = span parameter

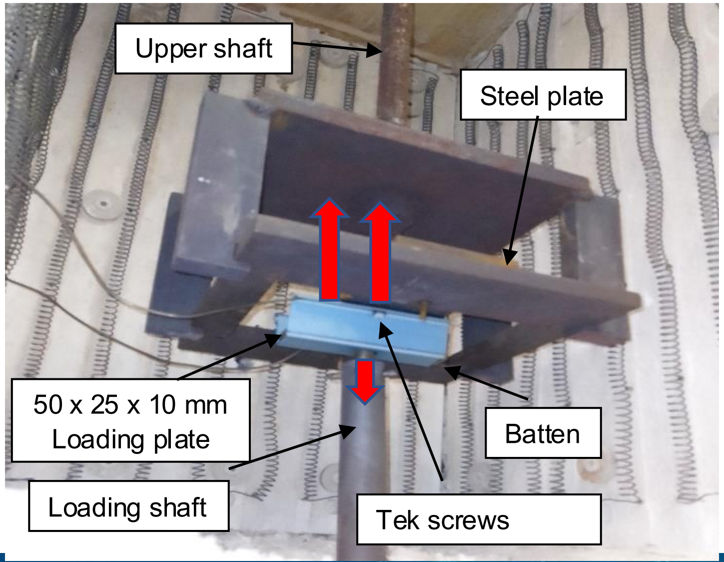
$$\frac{P_{ov,T}}{P_{ov,20}} = -3 \times 10^{-6} T^2 + 0.0011\text{T} + 0.966$$

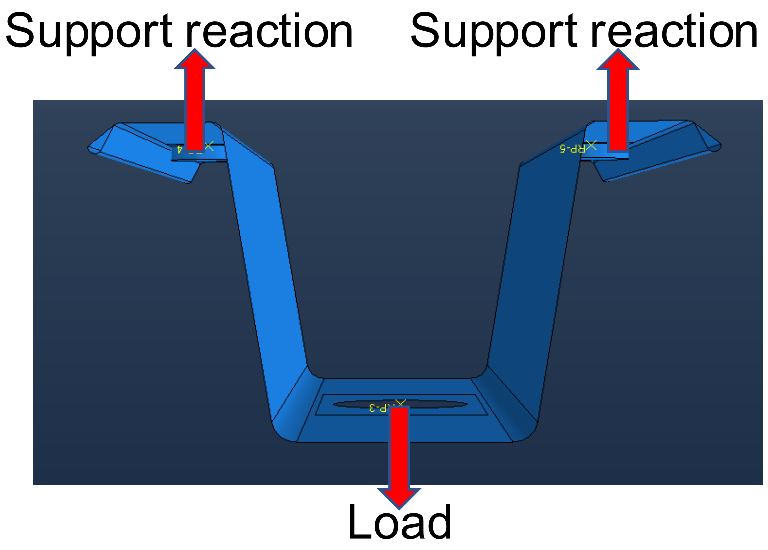


Pull-through Failures of Battens at Elevated Temperatures

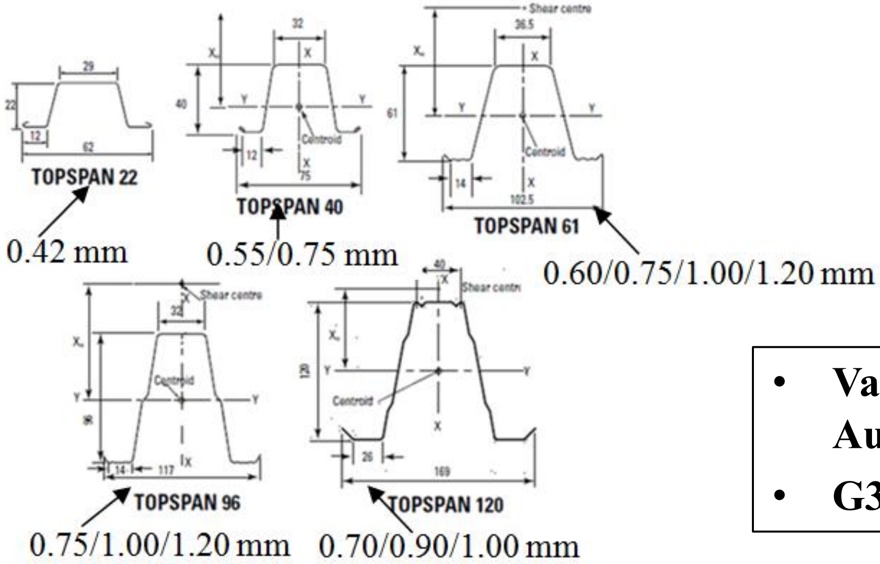
Test setup

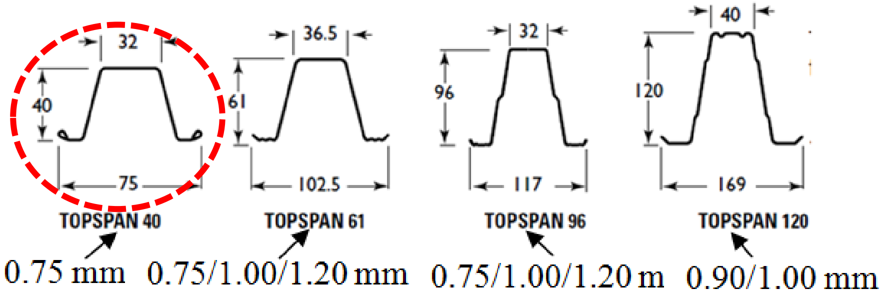
- 150 mm long battens were used inside the electric furnace to determine the pull-through capacities
- The batten was mounted to the steel plate using two screws, and the load was applied downward using the loading shaft.
- This test method only simulates tension action, not bending.
- Large scale two-span tests were also conducted



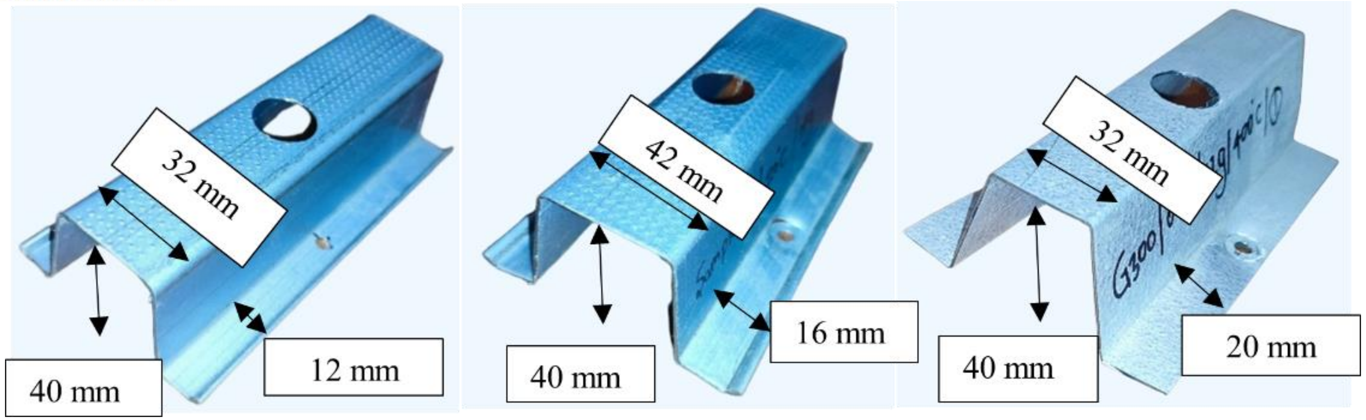


CFS batten profiles





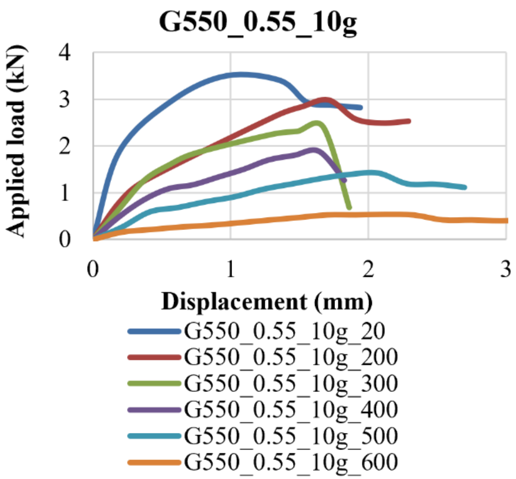
- **Various batten configurations, thicknesses & steel grades (G550 & G500 in Australia).**
- **G300 battens were fabricated at QUT workshop.**

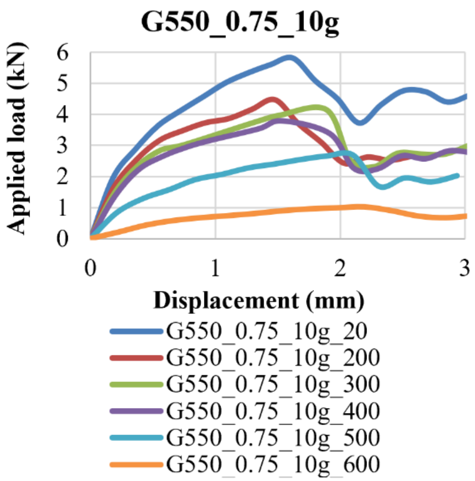


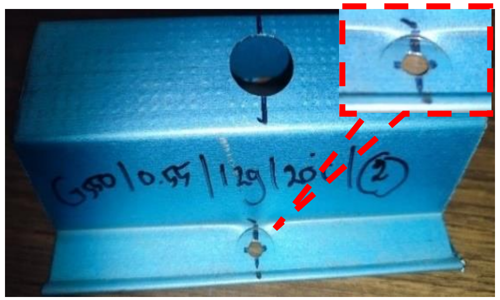
Pull-through Failures at Elevated Temperatures – Experimental Study

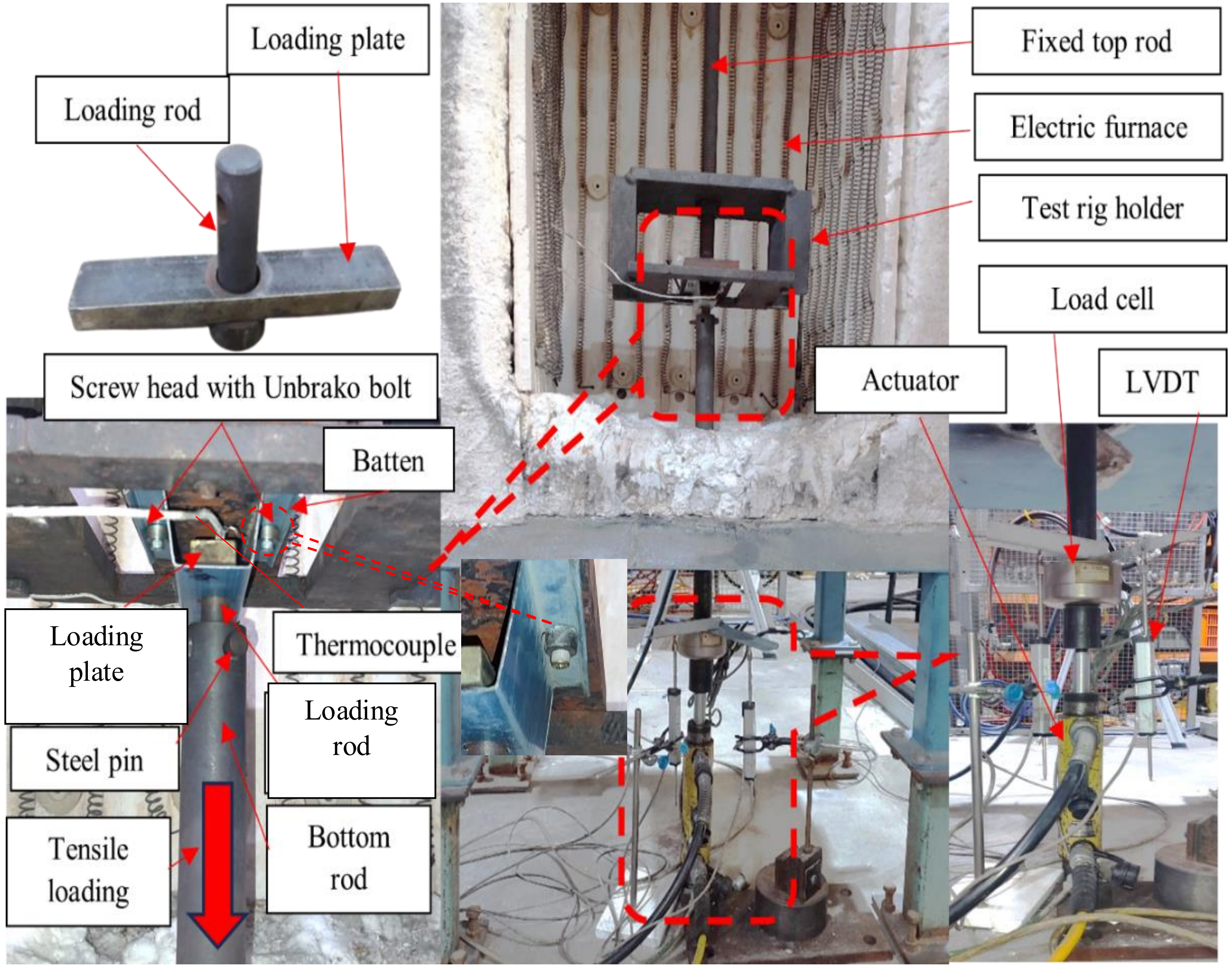
Short batten tests

- Only **tension action** is considered.
- Pull-through failure load = **Peak load / 2.**





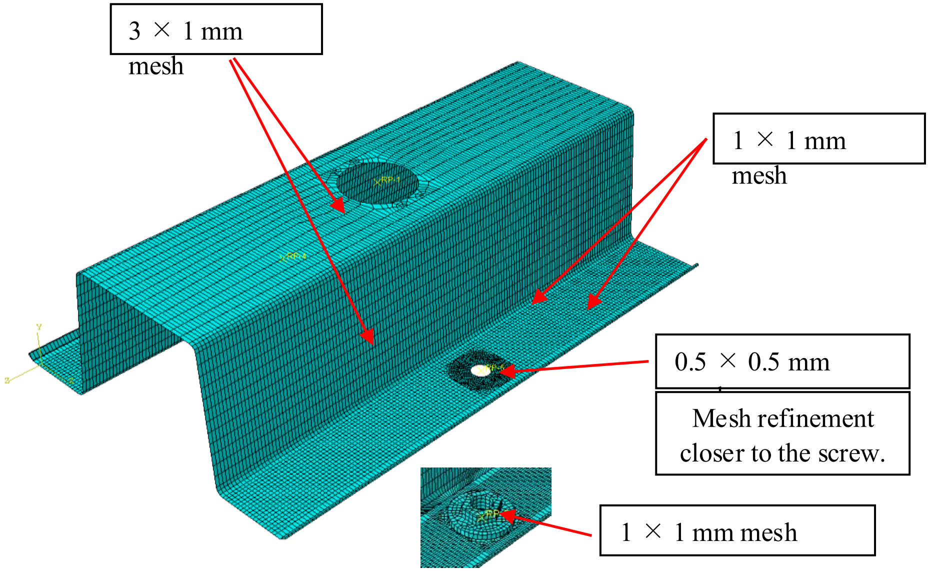


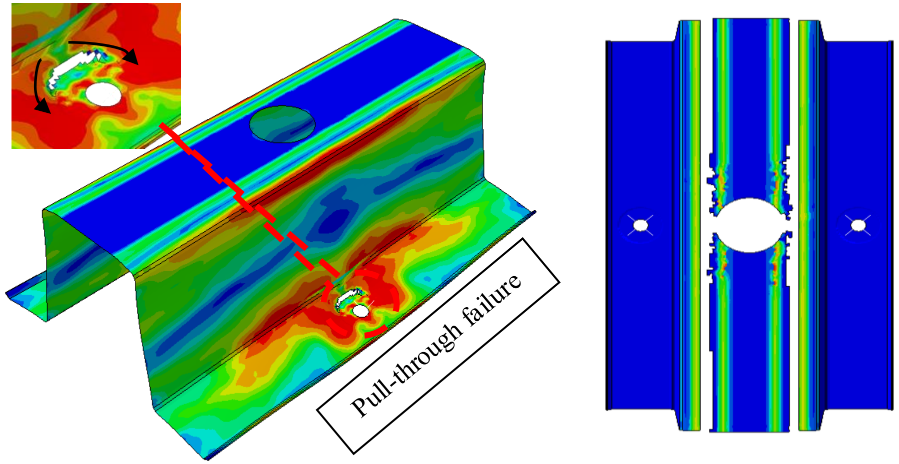


Pull-through Failures at Elevated Temperatures – Numerical Study

Mesh and step time control

- Batten -**S4R (shell)**
- Screw head – **C3D8R (solid)**
- Loading rate – **0.5 mm/s for static framework**

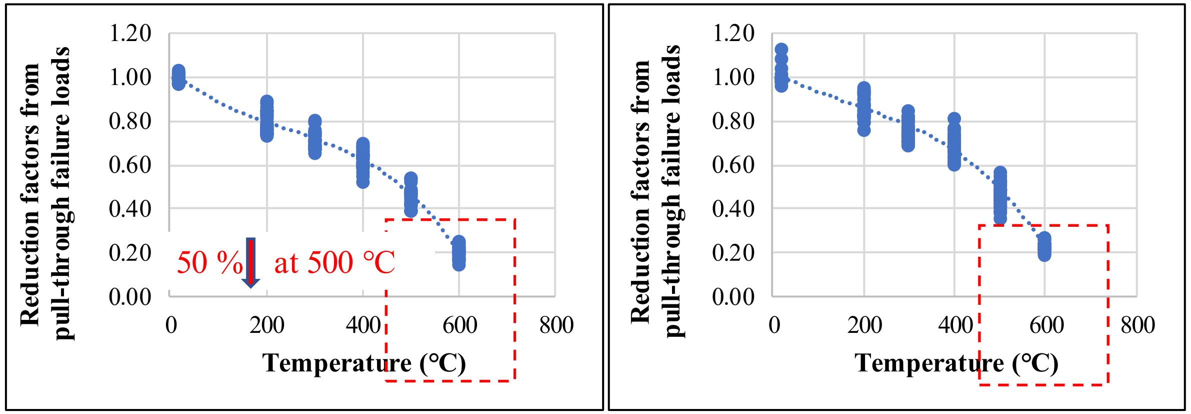




Pull-through Failures at Elevated Temperatures – Experimental & Numerical Study

Design

- For pull-through capacities at elevated temperatures.
  - **Reduction factor method.**
  - **Direct equation method.**



Reduction factor method

- ***RF* = Pull-through failure loads at elevated temperature/ Pull-through failure loads at ambient temperature.**
- a suitable equation was developed for reduction factors.

$$RF_{G550} = -6.424 \times 10^{-9} \times T^{3} + 4.663 \times 10^{-6} \times T^{2} - 1.865 \times 10^{-3} \times T + 1.036$$

$$RF_{G300} = -4.687 \times 10^{-9} \times T^{3} + 2.515 \times 10^{-6} \times T^{2} - 1.163 \times 10^{-3} \times T + 1.030$$

T – temperature and
RF – reduction factors

- Above equations should be used with a reliable **ambient temperature equation** to predict the pull-through capacities on batten screw connections at elevated temperatures.

$$P_{nov,\,20} = 8.6\, t^{2} f_{u} \text{ – G550/G500 steel battens}$$

$$P_{nov,\,20} = 3.07\, t^{1.4} d_{1}^{\,0.6} f_{u} \text{ – G300 steel battens}$$

Design

G550 battens:

$$P_{nov,T} = 0.10\, t^{1.49} d^{0.51} f_{u,T}^{0.51} E_T^{0.49}$$

G300 battens:

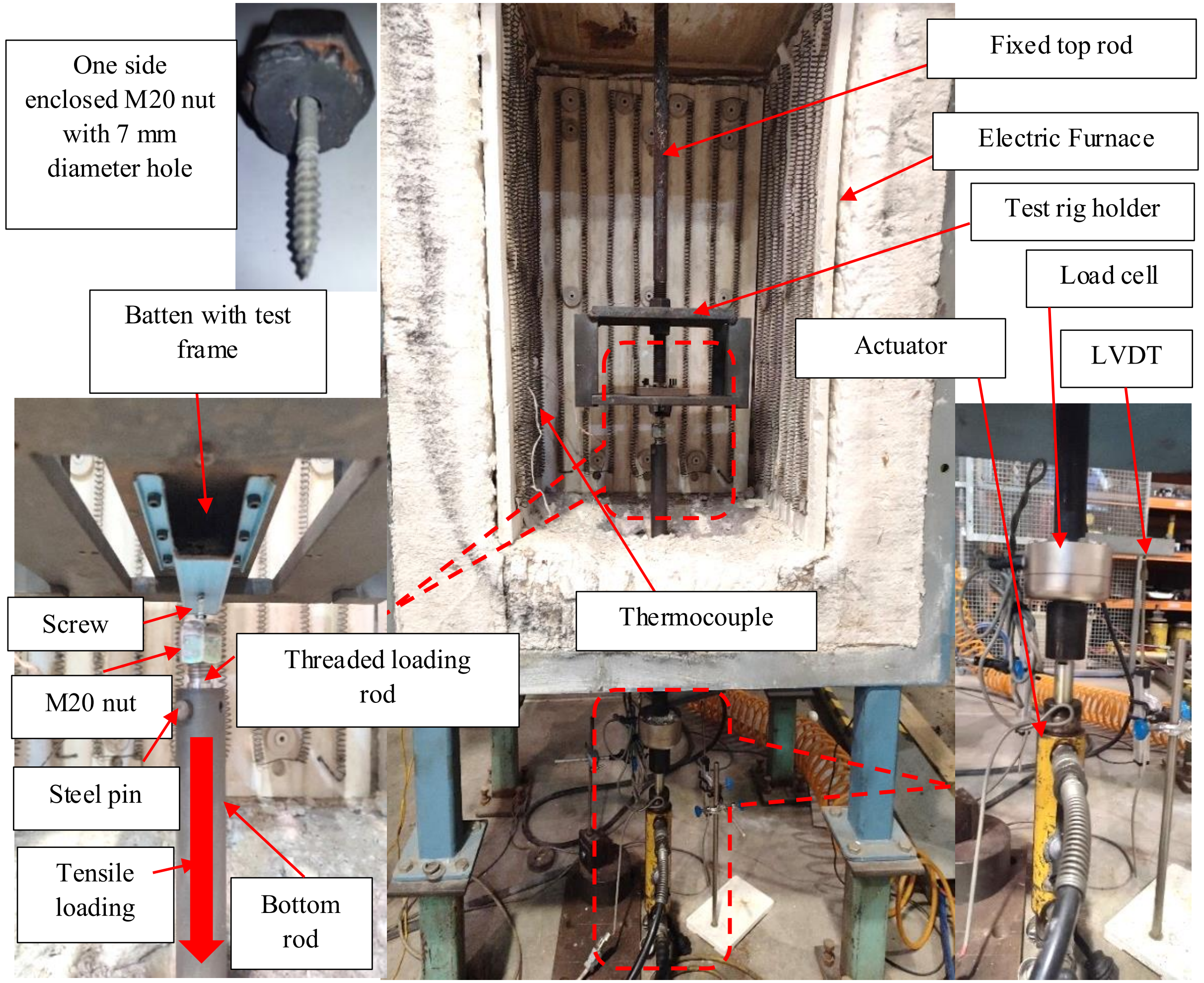
$$P_{nov,T} = 0.25\, t^{1.37} d^{0.63} f_{u,T}^{0.63} E_T^{0.37}$$

T- elevated temperature (ºC), t– batten thickness (mm), d– screw head diameter (mm), $f_{u,T}$ and E_T - ultimate strength and Young's modulus of CFS at elevated temperatures (MPa).11 mm ≤ d ≤ 14.5 mm, 0.55 mm ≤ t ≤ 0.95 mm for G550 battens and 0.55 mm ≤ t ≤ 1.00 mm for G300 battens.

Capacity reduction factor (ϕ)

- **0.60** is recommended using the approach given in AISI S100
- Based on error margin, ϕ, COV, **reduction factor equations** are recommended with ambient temperature equations.

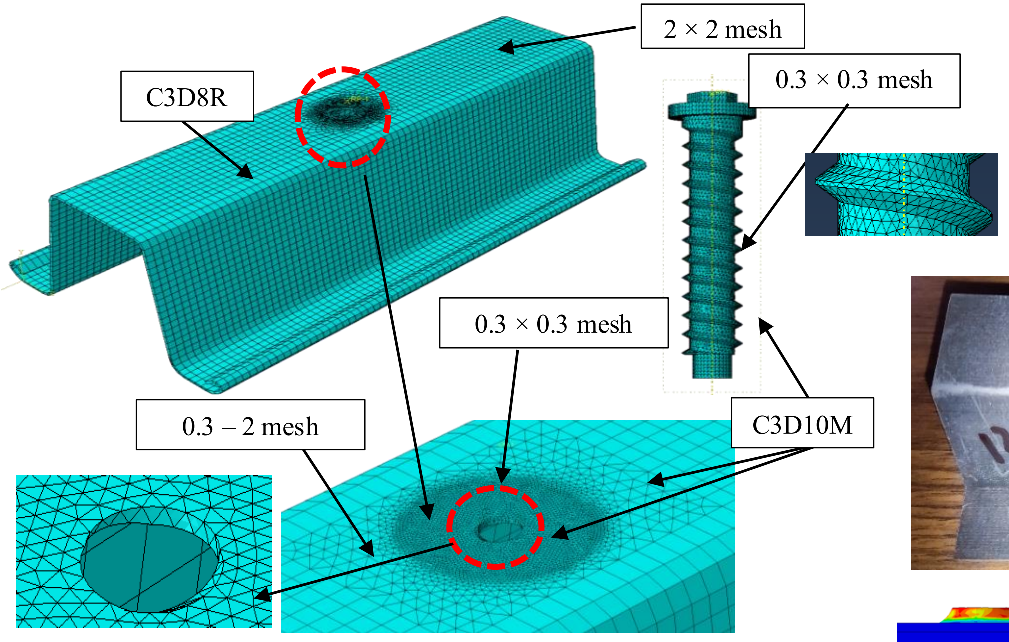
Pull-out Failures at Elevated Temperatures – Experimental Study

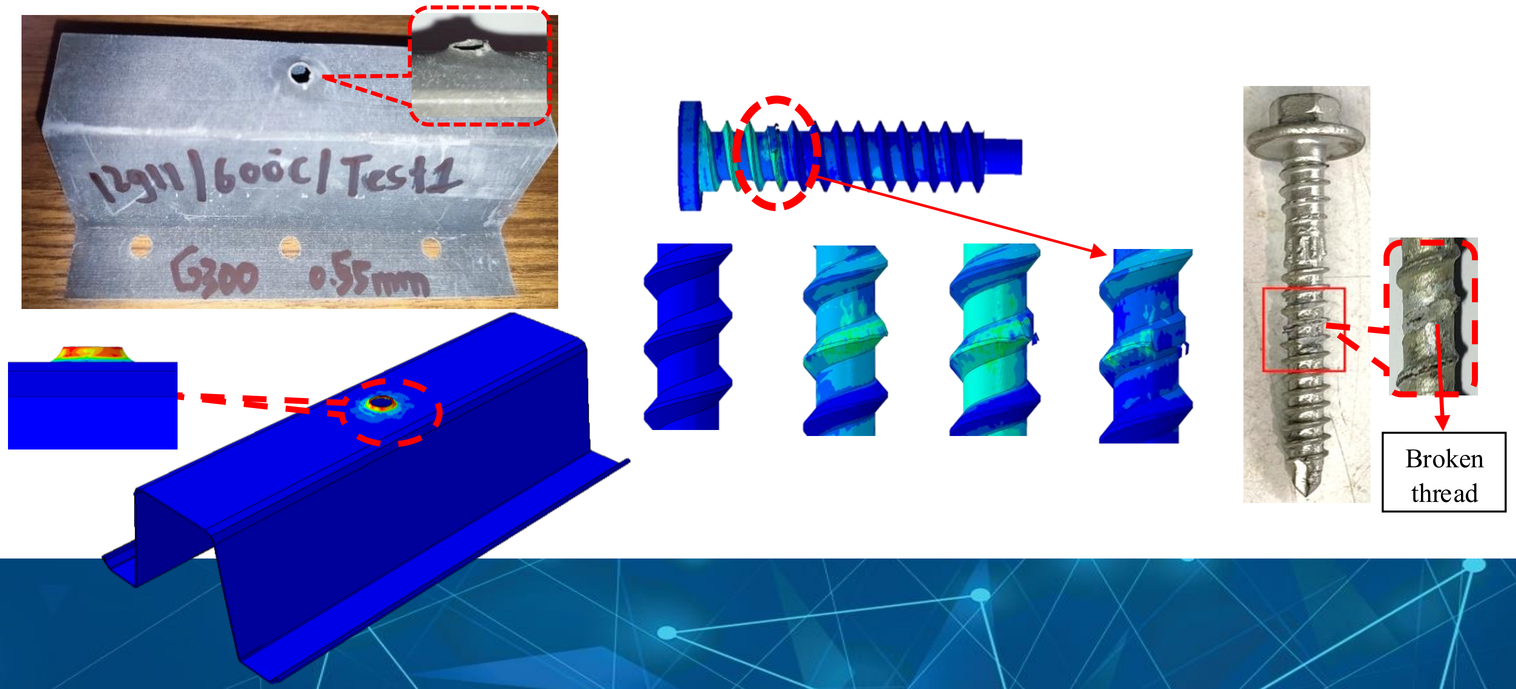


Pull-out Failures at Elevated Temperatures – Numerical Study

Mesh and step time control

- Loading rate – 2.5 mm/s for static framework

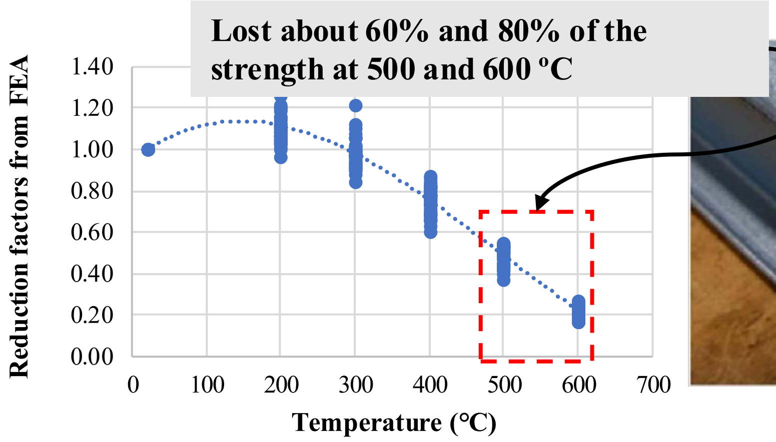


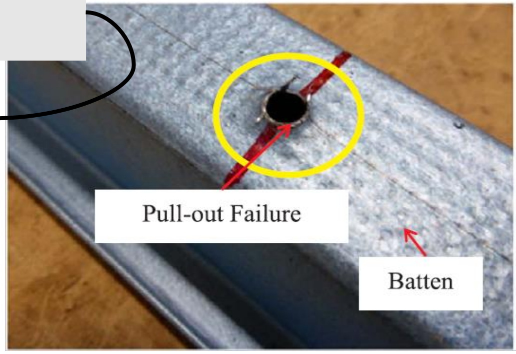


Pull-out Failures at Elevated Temperatures – Experimental & Numerical Studies

Design

- For pull-out capacities at elevated temperatures.
  - Reduction factor method
  - Direct equation method





<u>Reduction factor method</u>

- ***RF*= Pull-out failure loads at elevated temperature/ Pull-out failure loads at ambient temperature.**
- A suitable equation was developed for reduction factors.

T – temperature and RF – reduction factor

$$RF = k \times (6.92 \times 10^{-9}\, T^{3} - 1.0569 \times 10^{-5}\, T^{2} + 2.6113\, T + 0.951)$$

k = 0.99 for G500 and G550 battens (0.55 mm ≤ t ≤ 1.15 mm) and 1.01 for G300 battens (0.55 mm ≤ t ≤ 1.00 mm)

- Above equation should be used with a reliable **ambient temperature equation** to predict the pull-out capacities on batten screw connections at elevated temperatures.

$$P_{u,20} = 1.62\, k\, t^{1.3}\, d^{0.7}\, f_u\, [(d - d^*) / p]^{0.3}$$

Design

G550, G500 and G300 battens:

$$P_{u,T} = 0.29\, k\, t^{1.26}\, d^{0.74}\, f_{u,T}^{0.74}\, E_T^{0.26}\, [(d - d^*)/p]^{0.26}$$

$P_{u,T}$ –the pull-out capacity at elevated temperatures (N), T-elevated temperature (ºC), t –batten thickness (mm), d–screw outer diameter (mm), $f_{u,T}$ – Ultimate strength of CFS at elevated temperature (MPa). 0.55 mm ≤ t ≤ 1.15 mm for G550 and G500 battens and 0.55 mm ≤ t ≤ 1.00 mm for G300 battens. d^* = larger of d_1 or DD, ie. d_1 for Zips and T17 screws and DD for Tek screws, k – 0.97 for G550 and G500 battens and 1.07 for G300 battens.

Capacity reduction factor

- **0.55** is recommended as a capacity reduction factor using the approach given in AISI S100 (2016).
- In terms of error margin, ϕ, COV, **reduction factor equation** is recommended with ambient temperature equations.

Conclusion

- Details and results of investigations on the performance of several critical members used in the external steel building envelope were presented.
- Bushfire resistance depends on several localised screw connection failures.
- Bushfire enhanced wind actions combined with elevated temperature exposure have to be used in assessing the bushfire resistance of these critical members and connections.
- Designing buildings for bushfire conditions is a complex task as we do not know the true bushfire exposure in terms of fire and wind loads.
- However, using whatever we know, we must design the weakest elements of the external building envelope under the most realistic bushfire exposure conditions
- Safer buildings can be designed and built, by protecting the external building envelope. This research has provided critical input for designing safer, bushfire-resilient CFS cladding systems.

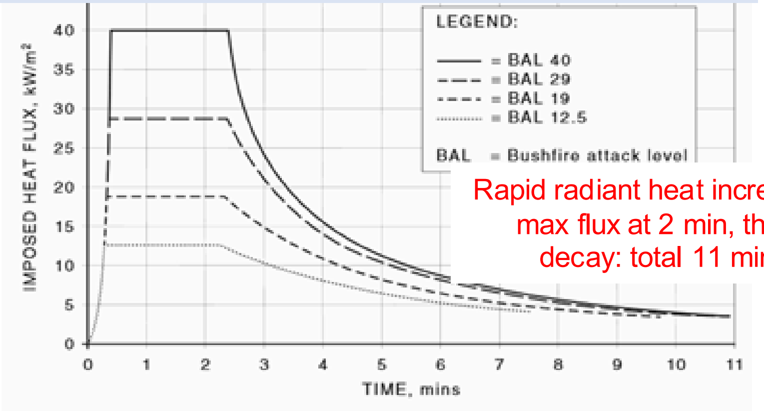
Hawaii Fires: The Red Lahaina House that survived Maui Fires

Simulating Bushfire Actions on Building Components

- Max temp in a bushfire flame zone can be up to 927℃ and radiant heat flux above 100 kW/m²
- Duration of bushfire exposure is significantly low, but the max temp and heat flux/ temperature gradient is significantly higher than standard fire (841℃ in 30 min vs 2 min)
- Heat increment rate is comparable to hydrocarbon fire curve in the first 5 min
- Bushfire exposure NASH standard: increasing radiant heat (pre- bushfire) followed by rapid rate of radiant heat increment in flame immersion & finally low radiant heat (to represent nearby burning fuel)

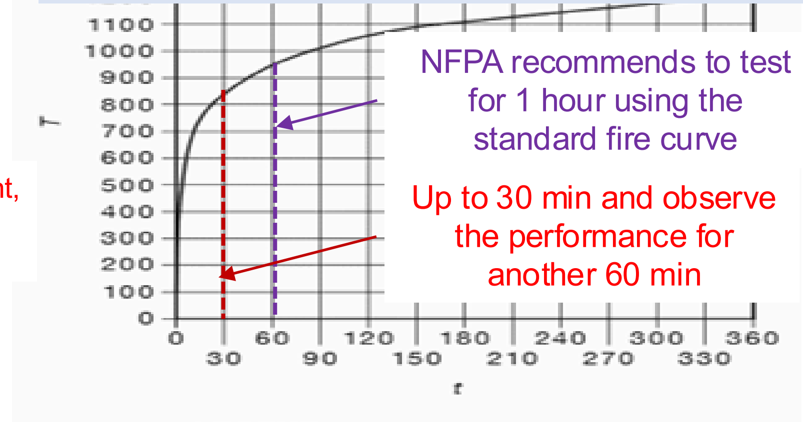
AS 1530.8.1

Used in testing the building elements exposed to radiant heat and small flaming sources

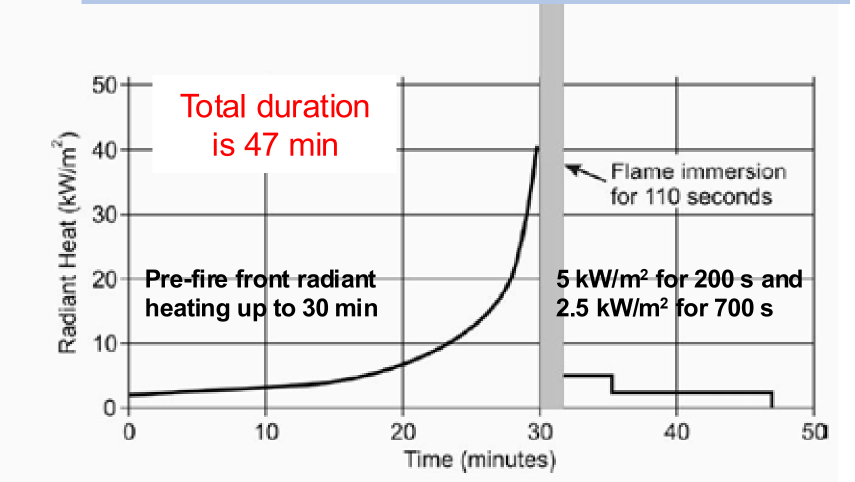


AS 1530.8.2 (as in AS 1530.4)

Used in testing the building elements exposed to large flaming sources



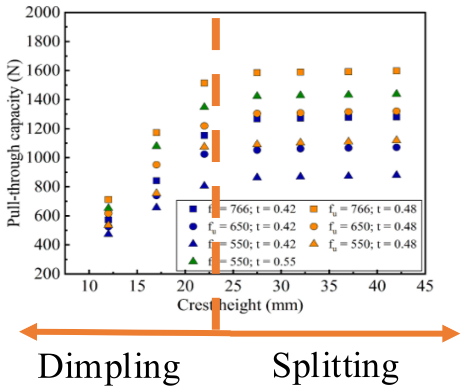
NASH Bushfire Standard

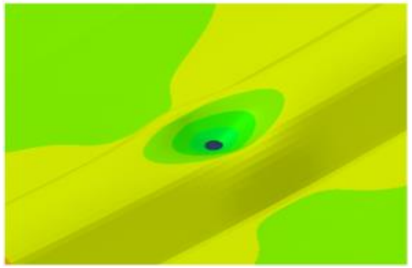


Geometry Parameters Controlling Splitting Failure in Trapezoidal Cladding with Wide Pans

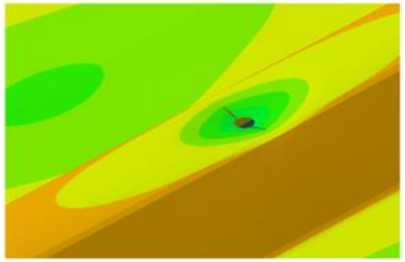
1. Crest height (h)

- When the crest height **h < 24 mm**, the sheet tends to experience **local dimpling around the fastener rather than splitting**.
- However, reducing **h** also leads to a **decrease in pull-through capacity**, which can be partially compensated by **optimising the crest width (w_c) and trough width (w_t)**.





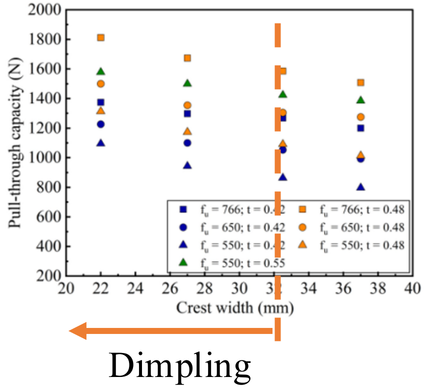
h=17 mm



h=42 mm

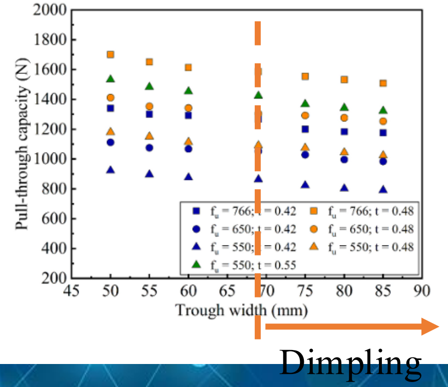
2. Crest width (w_c)

- **Reducing crest width** increases the tendency for **dimpling failure**. Smaller w_c also **improves pull-through capacity** due to increased local stiffness around the fastener.



3. Trough width (w_t)

- Increasing trough width promotes **dimpling behaviour but reduces pull-through capacity**.



Design provisions currently focus only on pull-through capacity, but do not consider failure mode transition between splitting and dimpling. This study demonstrates that cladding geometry can be tailored to control the failure mode.

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