

ULTIMATE BEHAVIOUR OF CLADDING ASSEMBLAGES IN INDUSTRIAL BUILDINGS

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INTRODUCTION

Profiled steel sheeting is widely used as cladding systems in industrial buildings. These systems are normally composed of thin-walled cold-formed steel profiles attached to steel purlins, or side-rails, which are connected to the column elements by means of simple fastener arrangements. Extensive research has been carried out on the response of cold-formed cladding systems under out of plane loading [e.g. 1,2] and codified recommendations are available to estimate their resistance under serviceability and ultimate limit states for the purpose of conventional design verifications [3]. Attention has also been placed recently on quantifying the degree of rotational flexibility offered by purlin-sheeting systems [e.g. 4-6]. Nevertheless, the ultimate response of such configurations involves complex interactions within the cladding-purlin-connection assemblage that need to be carefully examined in order to assess and quantify the large deformation response.

The study reported in this paper focuses on the inelastic response of industrial cladding systems which are designed and detailed according to conventional European practice. Selected results from a series of quasi-static tests performed within a wider collaborative project aimed at assessing the local and global static and dynamic behaviour of industrial building systems are presented. Due to the comparatively more robust response of typical industrial frame elements, the tests focus on the performance of cladding-purlin-column assemblages. The test layout and boundary conditions are described and the discussion is centred on key structural response parameters, namely stiffness, strength and failure conditions. Preliminary numerical assessments carried out with a view to providing further analytical and design studies are also outlined.

1 TESTING ARRANGEMENT AND SPECIMEN DETAILS

1.1 Experimental set-up

Fig. 1 shows the experimental set-up used for testing the cladding-purlin (or cladding-side rail) assemblages. Two 2.7 m long HEB-200 columns were employed to support the cladding system. Three purlins spanning 4.72 m were employed to fix the cladding sheeting to the horizontally laying columns. A general view of the experimental set-up is depicted in *Fig. 1b*. A symmetrical arrangement of nine Enerpac Jacks was employed to apply vertical loads at selected regions within the cladding-purlin-column assemblies as indicated by the shaded areas numbered 1 to 9 in *Fig. 1a*. Each Enerpac Jack had a maximum stroke of approximately 230 mm and a capacity of nearly 100 kN. Steel plates of 40 mm thickness were used to distribute the load to four 3/2"x3" wood laths of 100 mm length placed over the valleys of the trapezoidal cladding. The plate was connected to the vertical actuator through a spherical pin in order to allow rotations. Load cells were employed to monitor the forces in each of the nine Enerpack Jacks. The actuators were connected to a common manifold which was continually monitored in order to ensure an even distribution of pressure among all actuators. Finally, the HEB-200 columns were bolted to fixed supports at their extremes as indicated in *Fig. 1b*.

1.2 Specimen details

In total, 8 cladding-purlin sub-structure specimens were tested. A summary of the test series is given in *Table 1* which includes the cladding type, edge and mid purlin sections (see *Fig. 1a*) as well as the purlin-to-column connection detail. In this table, U refers to steel U-section, SHS to Square Hollow Section, and the connection details P1 to P4 are presented in *Fig. 3*. The reference system employed for the specimens follows the format L-TRXX-YYY. In this nomenclature, L represents a distinctive letter that characterizes the Specimen (from A to H), XX stands for the cladding type (35 for TR35 and 84 for TR84) and YYY represents the thickness of the cladding expressed in mm times 100 (e.g. 0.75 mm is represented as 075).

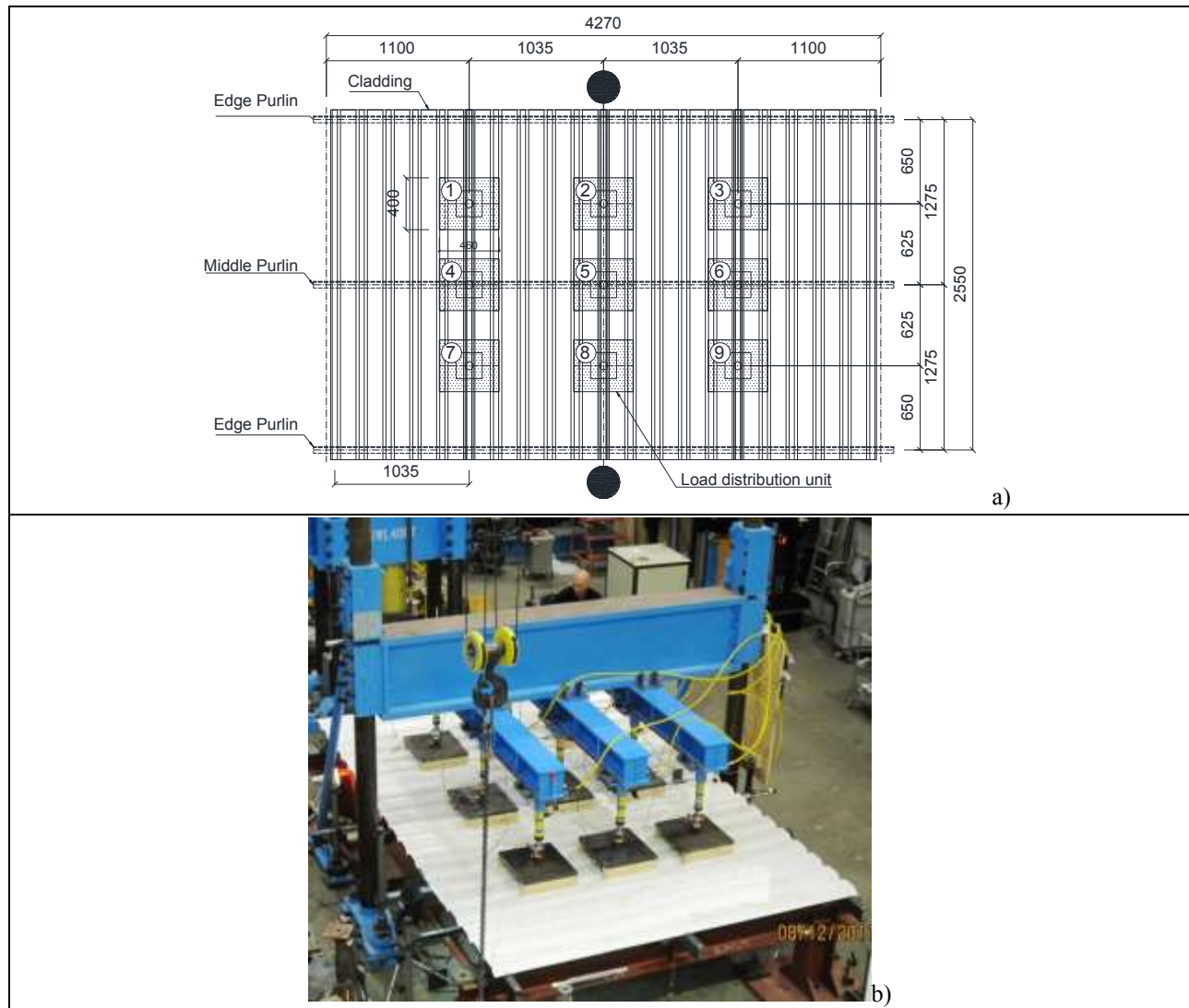


Fig. 1. Experimental set-up a) Test rig layout; b) Test rig view

Trapezoidal steel cladding sheets of different geometrical characteristics spanning over two 1.27 m spans were employed as summarized in *Table 1* and depicted in *Fig. 1a*. The cladding was fixed to the purlins by means of S-MP52Z 6,3x25 self-taping screws in all cases whereas four different bolted connection configurations were employed to attach the purlins to the column as presented in *Fig. 2* and *Table 1*. 20 mm thick replaceable steel plates bolted between the HEB-200 columns and the purlins were employed to avoid possible damage to the column section while enabling a practical experimental set-up. Complementary tests on single-sheeting assemblies and an extensive characterization of the shear behaviour of cladding-to-purlin connections were also carried out but are not reported herein for brevity.

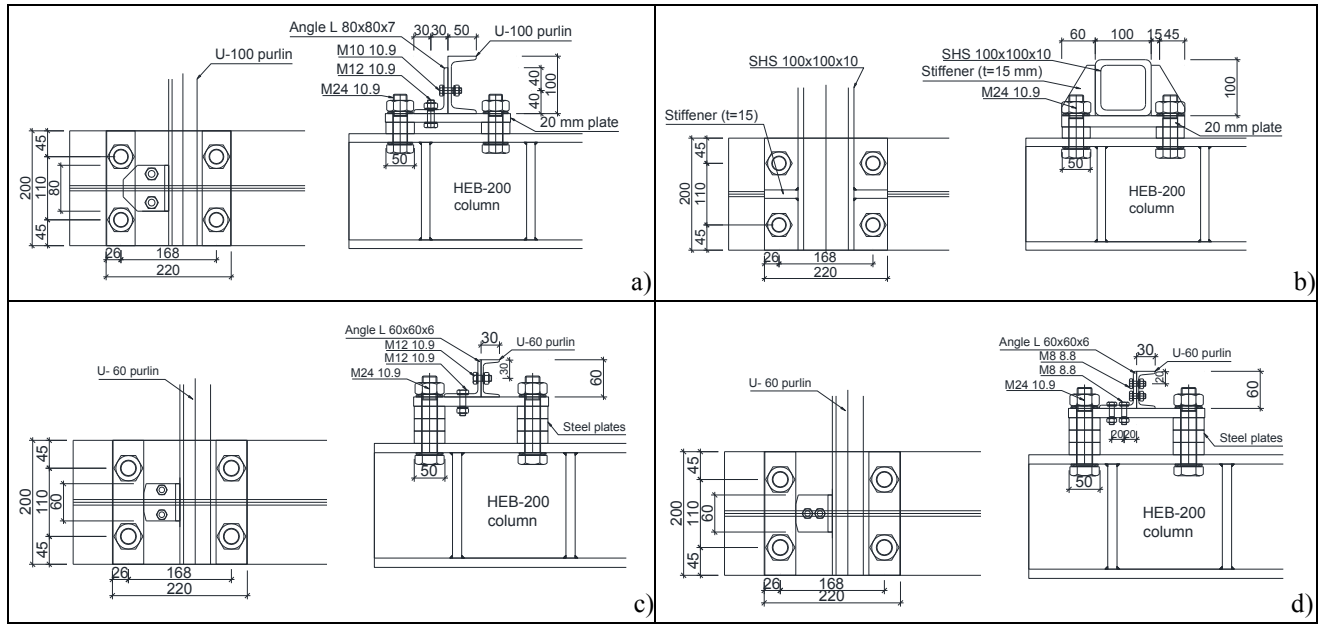


Fig. 2. Purlin-to-column connections a) Connection P1; b) Connection P2; c) Connection P3; d) Connection P4

Table 1. Summary of test specimens

Specimen	Cladding Type (Thickness)	Force in Actuators	Edge Purlin Sections	Middle Purlin Sections	Edge Purlin Connection Detail	Middle Purlin Connection Detail
A-TR35-100	TR 35/207 (1 mm)	1 - 9	U100	U100	P1	P1
B-TR35-100	TR 35/207 (1 mm)	1 - 3 and 7 - 9	U100	U100	P1	P1
C-TR35-100	TR 35/207 (1 mm)	1 - 3 and 7 - 9	SHS 100x10	U100	P2	P1
D-TR35-100	TR 35/207 (1 mm)	1 - 3 and 7 - 9	SHS 100x10	U60	P2	P3
E-TR35-075	TR 35/207 (0.75 mm)	1 - 3 and 7 - 9	SHS 100x10	U60	P2	P4
F-TR84-075	TR 84 (0.75 mm)	1 - 3 and 7 - 9	SHS 100x10	U100	P2	P1
G-TR84-150	TR 84 (1.5 mm)	1 - 3 and 7 - 9	SHS 100x10	U100	P2	P1
H-TR84-075	TR 84 (0.75 mm)	1 - 3 and 7 - 9	U100	U100	P1	P1

2 EXPERIMENTAL RESULTS AND OBSERVATIONS

Fig. 3 illustrates the typical deformation and damage states of different cladding components observed at the end of the tests. Significant bearing of the trapezoidal sheeting followed by shear fracture of the S-MP52Z 6,3x25 screws in the lateral cladding-to-purlin connection was observed in Specimens A-TR35-100, B-TR35-100, C-TR35-100, D-TR35-100 and F-TR84-075 and H-TR84-075 (see Fig. 3a, 3b and 3d). In all cases, significant plastic deformations were observed in the mid-purlin with residual mid-displacements of over 100 mm (as depicted in Fig. 3c for Specimen C-TR35-100). On the other hand, in the case of Specimen E-TR35-075 with a weaker mid-purlin-to-column connection (Detail P4 in Fig. 2d), large plastic deformations were concentrated in the angle component leading to failure of the two M8 bolts in tension (as depicted in Fig. 3e) at a mid-displacement of around 200 mm. Significant local buckling and plastic deformations also occurred throughout the trapezoidal sheeting as illustrated in Fig. 3f for Specimen H-TR84-075.



Fig. 3. Damage state at the end of tests a) residual deformations in B-TR35-100; b) bearing failure in B-TR35-100; c) plastic deformations in mid-purlin of Specimen D-TR35-100; d) screw failures in C-TR35-100; e) tension failure of bolts in purlin-to-column connection in E-TR35-100; f) localised deformations in H-TR84-075

Fig. 4 presents the total force versus displacement at mid-span of the 8 specimens under consideration grouped according to their cladding depth (TR35 in *Fig. 4a* and TR84 in *Fig. 4b*). This figure enables the observation of the influence of several parameters such as the number of loading points, cladding depth, cladding thickness, purlin-to-column connection and lateral restraint on the cladding assemblage response. The influence of the number of loading actuators can be assessed by comparing the response of Specimens A-TR35-100 and B-TR35-100 with 9 and 6 active actuators, respectively. It is evident from *Fig. 4* that no significant difference in the overall force-displacement response exists between the cases when all 9 actuators are employed and when only 6 of them (Actuators 1-3 and 7-9 in *Fig. 1a*) are active.

The influence of the degree of torsional flexibility provided by the lateral purlins can be observed by comparing the response of Specimens B-TR35-100 and C-TR35-100. Specimen B-TR35-100 incorporates U100 lateral purlins whereas Specimen C-TR35-100 utilizes 100x10 SHS sections in order to represent a limit case of full continuity between cladding sheeting providing significantly higher torsional restraint. As expected, there is a direct relationship between the out-of-plane stiffness and capacity of the cladding-purlin assemblage and the rotational restraint provided by the lateral purlins. As shown in *Fig. 4a*, an increment of nearly 10kN in the total out-of-plane force is evident for the stiffer Specimen C-TR35-100 in comparison with Specimen B-TR35-100 for a common mid-displacement of 40 mm. This difference in strength increases to +20kN at ultimate displacement levels (e.g. 140 mm at the mid-purlin). Likewise, a reduction of over 30% in the

initial stiffness is evident for Specimen D-TR35-100 which employs a U60 mid purlin in comparison with Specimen C-TR35-100 that incorporates a stiffer U100 mid-purlin. On the other hand, the depth of the trapezoidal sheeting has, as expected, a direct influence on the stiffness of the cladding-purlin assemblage. This can be established by comparing the response of Specimens B-TR35-100 and H-TR84-075 in Fig. 5a and 5b, respectively, where the only significant change is the type of cladding. In this case, the deeper TR84 cladding develops a stiffness of nearly 2.4 times that corresponding to the specimen with TR35, despite having a thinner section (0.75 mm as opposed to 1.00 mm thickness in Specimen B-TR35-100). Importantly, the same initial stiffness is developed by Specimen G-TR84-150 which incorporates thicker TR84 sheets (1.5 mm) and SHS lateral purlins, suggesting that the initial stiffness in those cases is largely governed by the mid-purlin. Notably, Specimen G-TR84-150 reached a peak load of nearly 230 kN (at about 80 mm) after which significant strength degradation occurred due to buckling of the TR84 profile.

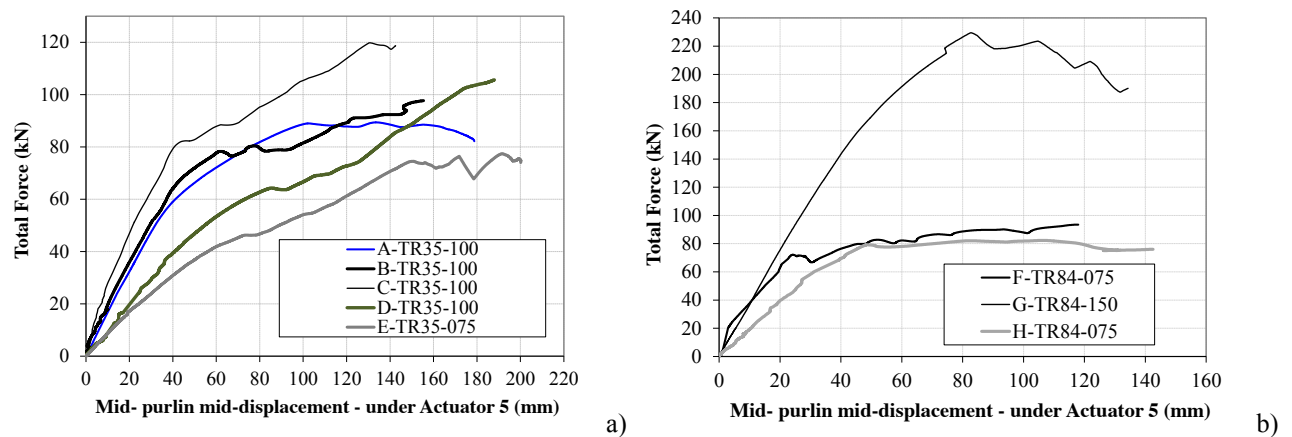


Fig. 4. Total force versus displacement response a) TR35; b) TR84

3 NUMERICAL ASSESSMENT

The results and observations from the experimental programme provided essential data for the validation of numerical and analytical models for cladding assemblages. To this end, detailed continuum finite element models were developed in the general purpose program ABAQUS [7]. Type S4R four-node shell elements were employed to model the cladding, purlin/side rail and angle components. The material properties corresponding to the different model components were obtained from coupon tests and idealised as bi-linear kinematic hardening stress-strain relationships. The boundary conditions and loading procedures adopted in the numerical analyses as well as the geometric details adopted replicate those of the test specimens. The S-MP 52 Z 6.3×25 self-tapping screws employed to connect the cladding to the purlin were idealised as bi-linear elastic-plastic Cartesian connectors with stiffness and yield capacity obtained from direct tension and shear tests on cladding-to-purlin connections carried out as part of the present study. Similarly, elastic-plastic Cartesian connectors were also employed to model the bolts in the purlin-to-column angle connections.

Figs. 5a and 5b present comparisons between the experimental force–displacement relationships and the corresponding FE predictions for selected cases on TR35 and TR84 cladding assemblages, respectively. It is evident from this plot that the FE models provide a good prediction of the experimental behaviour in terms of initial stiffness and ultimate capacity. The assessments also enabled a detailed insight into the mechanism and sequence of failure which were primarily associated with the cladding-to-purlin fasteners and/or the purlin-to-column connections.

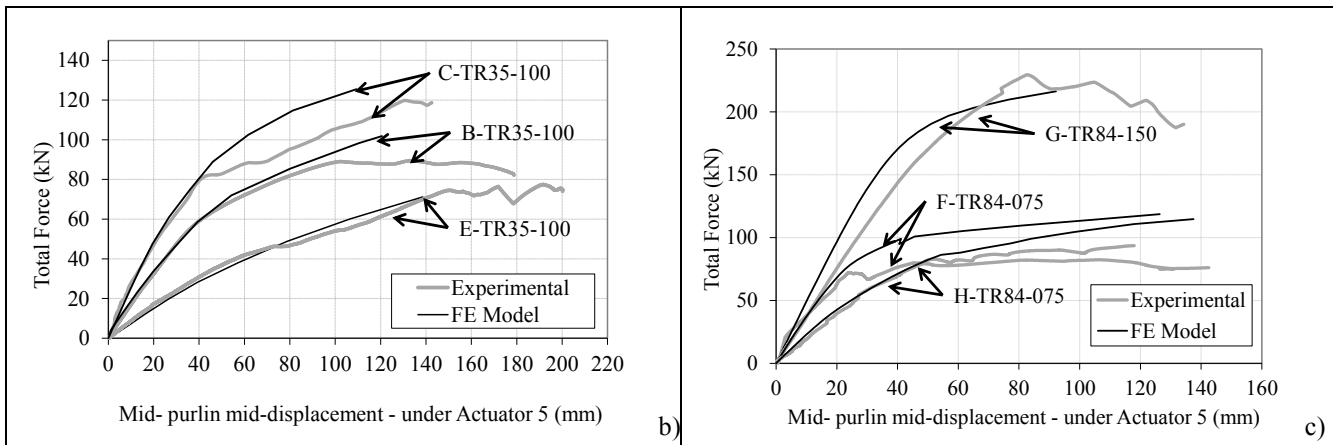


Fig. 5. Finite Element force-displacement estimation for: a) TR35; b) TR84

4 CONCLUDING REMARKS

This paper has examined the ultimate behaviour of industrial steel structures, with particular focus on the cladding/purlin/column assemblages. Selected tests from a wider experimental programme on representative sub-structures have been outlined. A discussion on the salient response characteristics such as stiffness, capacity and failure mechanisms has also been presented. The influence of cladding characteristics including purlin (or side rail) section, purlin-to-column connection and degree of rotational flexibility at the edge purlins on the stiffness and ultimate strength of cladding-purlin assemblages, has been highlighted. Finally, it has been illustrated that a reliable estimation of stiffness, capacity and ultimate resistance can be obtained by means of detailed FE models developed with a view to further practical design-oriented studies.

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