A Review on Stressed Skin Behaviour of Steel Façade Frame

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Abstract - *When it comes to physical and mechanical characteristics, steel is an excellent building material. By utilizing structural elements with relatively small cross sections, large spans and great heights can be covered. Considering the flexibility and slenderness of these girders, space stability of the whole bearing structure must also be addressed because of their flexibility and slenderness. Traditionally, spatial stability is created by bracings, which serve as a conduit for horizontal forces to be transmitted to the ground and to the foundations. In coordination with the main structure, it can behave as a diaphragm and contribute to its spatial stability. This paper aims to study all the features of stressed skin behavior of steel façade frame under varying structural conditions. Conclusions, recommendations, and diagrams provided in this study may be used to guide the application of the "stressed skin design concept" to the real world. The goal here is specifically to optimize fastener number, sheet profile height, height-to-length ratio of façade frames, and bearing capacity using FEA. All the studies concluded that the introduction of stressed skin behavior of steel façade frame can increase the strength of the structure.*

Key Words: Stressed skin behavior, steel façade frame, fasteners, cladding, spatial stability, diaphragm.

1. INTRODUCTION

Different types of bracings are used in traditional steel frame constructions to stabilise the primary bearing structure in space, retain the planned geometry and shape, and limit horizontal displacements of the slender elements. The "stressed skin design," on the other hand, stabilises the frame structure because the wall and roof cladding have significant in-plane stiffness. As a result, the cladding has the ability to accept and transfer horizontal forces operating on the structure while also providing spatial stability. However, putting this concept into action is challenging due to the difficulty in determining the stiffness of various types of corrugated sheets used as cladding, as well as the stiffness of the connections between the cladding and also the bearing steel framework. The shear or diaphragm panel is a section of the shear diaphragm made up of one or more corrugated sheeting separated by structural elements. European standards (EUROCODE EN 1993-1-3 2006) and steel structural design recommendations only address this concept in broad terms (ECCS 1995). Stressed skin design is quite possible, and it produces results that are comparable to or better than braced skin design in terms of stress and deformation of the structure [1,2].

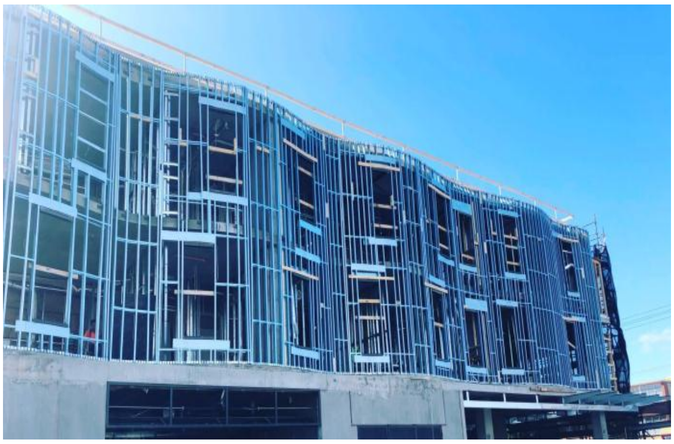
In reality, whether or not the diaphragm effect is considered, it is always there in a building. Economic studies conducted in Europe by organizations such as the European Convention for Constructional Steelwork (ECCS) or the Constructional Steel Research and Development Organization (CONSTRADO, 1976) revealed savings of up to 10% of the total cost of the steel structure when the diaphragm effect was taken into account in the design. The fundamental function of roof and wall cladding systems is to keep the structure dry and airtight, while the diaphragm effect transforms them into major structural components [5].

1.1 Steel façade frame

Any largely vertical aspect of a building envelope, such as an exterior wall, is referred to as a facade. A façade is one side of a building's exterior, usually the front, but also the sides and back on occasion. Steel is frequently used in the construction of façade frameworks. The lateral and vertical resistance to exterior elements such as wind is enhanced by a façade steel frame.

1.2 Cladding

Cladding is the process of applying one material above another to create a skin or layer, which can be both decorative and practical. Its purpose is to compliment the building's architectural design while also providing shelter from rain, wind, snow, and other external factors.



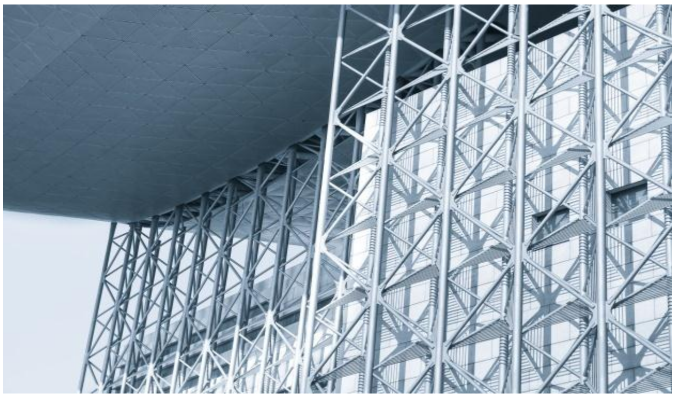


Fig -1: Steel façade frame before cladding

Fig -1: Steel façade frame after cladding

1.3 Stressed skin design

The cladding can operate as a diaphragm and contribute to the spatial stability of the primary structure, enabling the so-called stressed skin design concept to be implemented. In other words, the resistance and stiffness of frames are influenced by the resistance and stiffness of roofing, flooring, and side cladding panels. As a result, such panels are referred to as "shear diaphragms" or "simply diaphragms", in the Europe, they are referred to as "stressed skin design". As a shear diaphragm, profiled steel sheeting is highly effective when used as roof sheeting or decking, floor decking, or side cladding [3,4]. The benefits of stressed skin design are:

• Calculated frame stresses and deformations are typically substantially lower than bare frame stresses and deflections.

• Stresses and deflections calculated and observed agree, making the design more realistic.

• Bracing in the roof plane is removed or the frame size is lowered.

• By diaphragm action, stressed skin structures utilise the cladding to withstand lateral load.

2. STRESS AND DEFORMATION ANALYSIS

The stressed skin idea has been thoroughly confirmed, based on the fact that the façade and roof cladding of a building with a steel bearing structure have significant in-plane stiffness, can receive and transmit lateral forces acting on the building, and offer structural stability of the structure. We determined that the cladding contributed to the overall stiffness of the entire façade frame, as well as the prominent stressed skin behavior, by comparing the findings of the frame without cladding and the cladded frames. The number and gauge of fastening devices determine the strength and deformability of the investigated façade steel structure, confirming earlier findings. Fastening of the cladding to the steel frame in troughs is along horizontal direction (connections to the beams) rather than the vertical direction (connections to the columns) is the dominant influence. The process of horizontal force transfer from the frame to the cladding, which occurs primarily through shear of the fastening mechanisms between the cladding and the frame beam, rather than the frame column, is the reason for this. As a result, the results of the analyses may be used to identify the appropriate number and gauge of fastening devices.

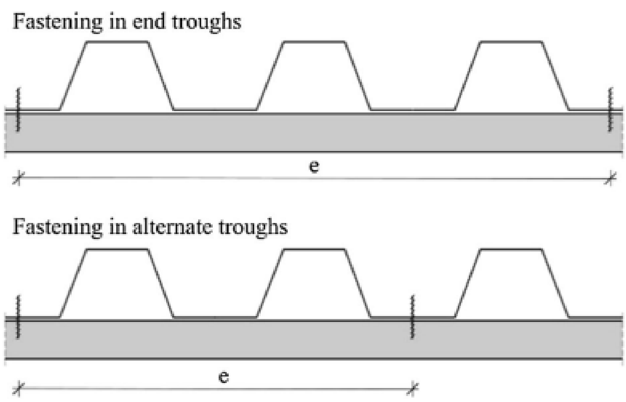


Fig -3: Different fastening positions

The fastening systems, frame dimensions, type of cladding, and other factors all influence the strength and deformability of the stressed skin design of the investigated façade steel frame.

3. LOAD CARRYING CAPACITY

In terms of load carrying capacity, the shear resistance of roof panels is determined by the capacity of the seam fasteners, the kind and thickness of the sheeting, and the side fastening. From two-sided fastenings to four-sided fastenings, the shear capability can increase fourfold [5].

A summary of the load-carrying capacities of panels is provided in table 1. The proportional limit in each configuration is indicated by the "Linear range" column; as a result, the previously mentioned flexibility values can be assured until these load limitations are met. In general, the two-skin designs with narrower trapezoidal sheet profiles had the higher load-carrying capacity values. In single skinned systems, using a lower trapezoidal sheet profile (LTP20) increased load-carrying capacity by 30% over using a larger trapezoidal sheet profile (LTP30) (LTP45). The reason for this could be related to the quantity of fixings available, as the form profile of LTP20 sheeting is intended to have much more corrugations than LTP45 sheeting, allowing for more fixings to be used on LTP20 sheets than on LTP45 sheets. The number of fixes has a significant impact on behaviour: reducing the number of fastenings by 50% results in a 16–36% reduction in load-carrying capacity. Purlin size and thickness are increased by 10–40% to boost load carrying ability [3].

Table -1: Measured load carrying capacities

Test No.	Purlins	Trapezoidal sheeting	Fixing number in troughs	Sheeting	Linear range (kN)	Load carrying capacity (kN)
1	Z200/1.5	LTP20/0.5	Every	Single	10.22	19.04
2			Alternate	Single	7.45	11.52
3				Two skin	17.23	22.02
4		LTP45/0.5	Every	Single	7.81	12.69
5			Alternate	Single	7.22	9.71
6				Two skin	11.96	17.58
7	Z250/2.0	LTP20/0.5	Every	Single	18.25	23.65
8			Alternate	Single	12.45	17.41
9				Two skin	25.67	33.03
10		LTP45/0.5	Every	Single	13.66	15.56
11			Alternate	Single	9.21	11.96
12				Two skin	16.82	22.35
13	Z300/2.0	LTP20/0.5	Every	Single	17.71	22.41
14			Alternate	Single	12.85	16.91
15				Two skin	24.75	28.83
16		LTP45/0.5	Every	Single	14.22	16.15
17			Alternate	Single	9.82	12.21
18				Two skin	18.85	22.87

4. CRACK PATTERN

As illustrated in Fig. 4(a) and (b), fatigue failures created two common types of fracture patterns: crease and star type. Cracks originating at crease points away from the fasteners hole and cracks originating at the screw hole are the two types of crease and star crack patterns [6].

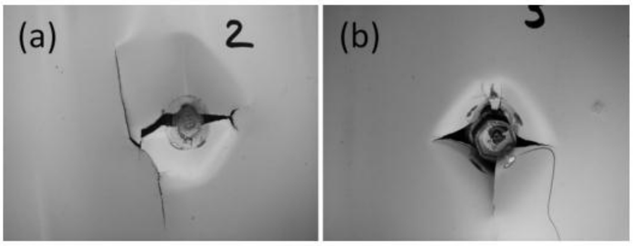


Fig -4: Example of (a) crease type (b) star type

Mahendran [7] made a similar observation using line load test loading systems. According to Henderson [8], the crease fractures are divided into two patterns: 'H' and 'T.'

For Pmax, Fig. 6 illustrates the number of cycles during which a crack is initiated and the number of cycles during which it fails. Fig 6 also depicts the crack types at failure for each test, which can be linked to the load ratio R and ultimate load per cycle as indicated in Fig 5. When a crack larger than 1.0 mm is discovered, it is called crack initiation. The numbers of cycles for commencement and failure in the material being tested may not be the same. They denote the number of cycles required for the initiation and failure of any of the four "completely loaded" screws. For crease type cracks, a crack begins earlier in the cycle counts, with cracks occurring at the crease points away from the screw head. These fractures have a higher stress each cycle than the star cracks that occur beneath the screw head. Furthermore, failure from crease type cracks necessitates much longer cracks with correspondingly quicker development rates [6].

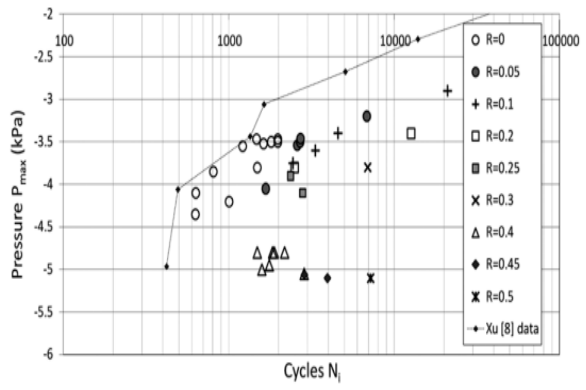


Fig -5: Peak pressure with numbers of cycles to failure

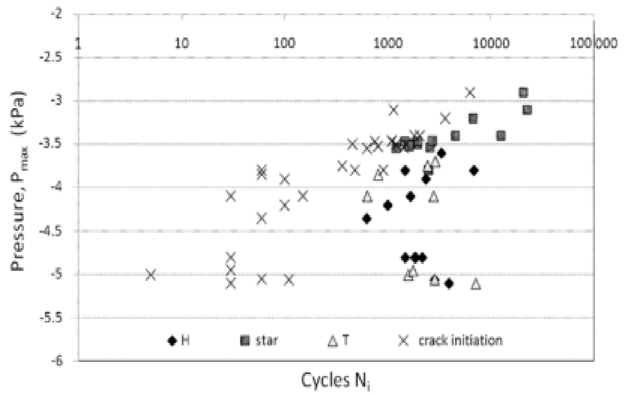


Fig -6: Number of cycles to crack initiation and to failure for star and crease ('H' and 'T') type cracks.

4.1 Crease type crack

Crease points formed around the edges of the distorted crests under loads greater than the corrugated cladding's local plastic deformation (LPD) strength. Cracks began at these crease locations and grew outwards, forming a 'X' shape longitudinally and transversely [6].

4.2 Star type crack

Under the flexible seal that fits between the underneath of the screw head and the cladding as a weather wrap on the screw holes, star cracks appear in the cladding at the screw hole. During the static loading experiments, cracks occurred at lower pressures than the pressures recorded for local plastic deformation [6].

5. SHEAR FLEXIBILITY

A further study programme is intended to improve and extend the current design techniques, based on an analysis of the available research findings and design recommendations on stressed skin effect, as well as preliminary numerical calculations. The research program's purpose is to investigate the stiffening effect of nonstandard diaphragm configurations that avoid the use of seam fasteners and are often used in everyday building throughout Europe. The present literature examines [9]and evaluates the shear flexibility data, including a comparison of test and computed results. The stiffening impact of the analysed nonstandard diaphragms is shown to be underestimated by the ECCS formulas. The discrepancies range from 3% to 100%, with considerable scattering. The usefulness of present formulae is limited to standard setups, and the primary goal of this study is to expand the sphere of applicability of current formulae so that they can be used in nonstandard situations. More research is needed to identify the variables that influence the shear stiffness of non-standard diaphragm configurations. The effect of diaphragm height and fixing number, as well as structural components (purlins, bracing, and sheeting) on shear flexibility, are discussed further.

5.1 Effect of section size and no. of fixings

The impact of section size and the number of fasteners on shear flexibility is examined in depth. In fully clad instances, raising the section height of purlins increases shear flexibility by 6–109 %. In those cases where no bracings were used, a smaller rise of 1–55 % was recorded. A contrasting trend was observed in roof cladded and braced configurations: increasing purlin height leads to an increase in flexibility of 11–44 %. In some circumstances, removing the bracing allows for more flexibility. The flexibility of a trapezoidal section increases by up to 53% when the height of the section is increased. This conclusion does not apply to diaphragms that are only found in the roof. Shear flexibility is mostly influenced by the amount of fixes. When using higher sheets, the flexibility is reduced by 17–40%, implying that double the number of fixes is used. By using smaller sheet heights, this range might vary between 2% and 30% [10,14].

5.2 Effect of structural components

When comparing the effect of purlins on the structure's shear flexibility, it may be concluded that roof purlins stiffen the building more (2–6%) than wall purlins. The use of roof bracing increases hall stiffness by 2–3 times, whereas the use of roof and wall bracing makes the structure 8–10 times stiffer. This demonstrates that bracing has a significant impact on the shear rigidity of the structure. The use of internal and external cladding reduces shear flexibility by 40–78%, demonstrating the non-negligible stiffening impact of steel cladding. Internal cladding has a minor impact on shear flexibility as compared to external sheets. At modest purlin profiled cases, this value decreases by 1% to 5%, whereas at high profiled cases, it decreases by 1–15 %. The results of the diaphragm effect show that the stiffening impact of diaphragms is comparable to the stiffening effect of bracing in nonstandard circumstances.

The findings indicated that the influence of purlins in both the wall and the roof reduces shear flexibility by 17–40%.

The installation of wall covering reduces flexibility by between 24 and 87 %. Cladding plus bracing of the structure reduces flexibility by 27–86%, while bracing alone reduces flexibility by 57–86% in unclad frames. The influence of inner cladding on flexibility is reduced by 23–75 % [10,14].

6. EFFECT OF OVERHANG LENGTH VARIATION OF STEEL ROOF CLADDING

The effects of varying overhang lengths (150 mm and 300 mm) on the pull-through capability of corrugated and trapezoid roof claddings were explored by Nasirah et.al. A hydraulic testing machine was used to conduct a new easy test procedure using single-span cladding under static uplift pressure. The pull-through capacity of corrugated roof cladding was greater than that of trapezoidal roof cladding, according to the findings. Furthermore, as the overhang length was extended, the steel cladding's pull-through capacity decreased for both cladding profiles. Localized dimpling failure of corrugated cladding and cross-sectional deformation of trapezoidal roof cladding were observed as a result of this study. In conclusion, increased roof cladding length decreased pull-through capacity and applied load for both cladding profiles.

For the 150 mm and 300 mm overhang lengths, respectively, corrugated roof cladding produced an average maximum fastener reaction force of 1.47 kN and 0.46 kN, as well as an average maximum deflection of 80.25 mm and 58.75 mm. The fastener response force of the corrugated roof cladding with 150 mm and 300 mm overhand length was 53 % and 72 % for trapezoidal roof cladding, respectively. The deflection of trapezoidal roof cladding with 150 mm and 300 mm overhang lengths, on the other hand, was 23% and 38% larger than that of corrugated roof cladding, respectively. Under static wind uplift stress, corrugated roof claddings had local dimpling failure, whereas trapezoidal roof cladding experienced cross-sectional deformation of the discretely fastened roofing. The length of the overhang, the amount of uplift loading, and the amount of deflection all have a relationship. Increased overhang length resulted in a reduced uplift force beneath the overhanging roof as well as lesser deflection for both cladding profiles. Corrugated roof cladding had a higher fastener reaction force (pull-through capacity) and maximum applied load than trapezoidal roof cladding. The deflection of trapezoidal roof cladding, on the other hand, is greater than that of corrugated roof cladding. With increasing roof cladding length for both cladding profiles, the maximum fastener response force and applied load decreased [12].

7. COST ANALYSIS OF THE STRUCTURE

One of the advantages of using the stressed skin design is that it is cost effective. The stressed skin structure was found to be 8-15 % less expensive than the braced structure in this study [2]. When compared to a design that ignores stressed-skin action, the material cost of the internal frame can be lowered by as much as 53% for a building with two internal frames [13]. The findings of the least cost optimisation show that when stressed-skin activity is taken into consideration, the cost of the internal frame for "square-shaped" buildings can be cut in half. It's important to remember that this is a least cost optimization, not a minimum weight optimization [11].

8. PRACTICAL APPLICATION OF STRESSED SKIN DESIGN CONCEPT

The initial stages of stressed skin design coincided with a massive, government-led construction boom that included prominent schools and hospitals. Many of these were made with the help of systems, and a lot of effort went into incorporating stressed skin design into them. This was done not simply to save money on cross bracing, but also to make the system easier to understand in terms of design calculations and component count. Standard diaphragm designs might be employed without the requirement for complex calculations thanks to design tables. The contractor must then select his own decking profile and fastener specifications and demonstrate that they meet the performance requirements, which include the load in the roof plane that must be resisted and stressed skin design. The aluminium liner trays in the roofs of the stands at both the Millennium Stadium in Manchester and the new stadium for Arsenal Football Club are two recent significant instances of this technology [15].

9. CONCLUSIONS

The fastening systems, frame dimensions, type of cladding, and other factors all influence the strength and deformability of the stressed skin design of the investigated façade steel frame. Stressed skin design seems to be quite possible, and it produces satisfactory results in terms of structural stress and deformation, equal to or better than braced design. We found that the cladding contributed significantly to the overall stiffness of the entire façade frame, as well as the prominent stressed skin behaviour, by comparing the findings of the frame without cladding and the cladded frames. The findings of this study, as well as the conclusions, recommendations, and guiding illustrations, can be used as design guides when using the "stressed skin design concept." This refers to the number of fasteners used, the thickness of the sheets, the height-to-length ratio of the façade frame, and the bearing capacity of such frames.

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