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STATE-OF THE-ART ON THE CORRUGATED SHEETS ACTING AS A DIAPHRAGM IN SINGLE STOREY FRAME STRUCTURES

BY

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Abstract. Nowadays there is a growing demand in building single-storey frame structures because of the benefits they possess in regarding to the large and open spaces that makes them well suited for socio-economic, cultural or industrial activities. Regarding the solution used for cladding it has become a construction standard for the execution to be accomplished either by corrugated steel sheets or sandwich panels. During the last decades there has been a lot of academic research focusing the attention on using the corrugated sheets as a stress bearing element for structures. It has been recognized that the building framework becomes strengthened and stiffened with the addition of floors, envelope and roof. By taking the cladding into account the structural engineer can better predict the actual response of the building. The side cladding is very effective as a shear diaphragm and with proper attachment to the frame members using mechanical fasteners (or rarely by welding) it may be used as a structural component. In this regard the literature provides substantially verified full scale tests that are also proven by site experience of many building designs.

Keywords: corrugated sheet; frame stiffness; sheet cladding; building envelope; stressed skin design.

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1. Introduction

Single-storey precast concrete frame buildings are currently in very high demand given that this type of structure is designed to embody thousands or even tens of thousands of people every day. The need for structural systems with large generous area is constantly increasing. The wide, ventilated and open spaces provided by single-storey frame structures makes them suitable for organizing the economic production flows for logistics, storage facilities, malls, and other socio-economic activities. Also the dynamics of society often steer building spaces to be shifted from one destination to another and the single-storey buildings have the advantage that they can be reconverted at low costs in a relatively short time.

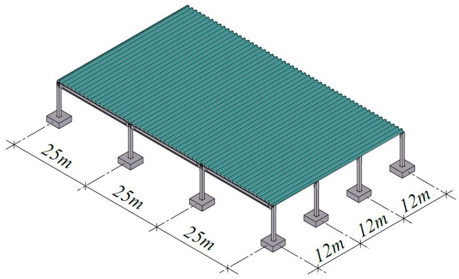


Fig. 1 – Typical single-storey frame structure opening.

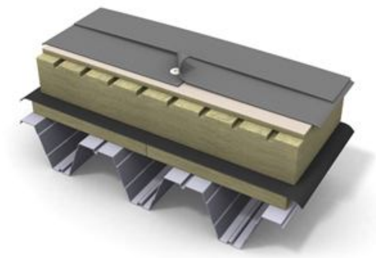


Fig. 2 – Typical single-storey envelope detail (Paroc Group www.paroc.com).

It has been noted that concerning the surface that unloads on a column, this has grown steadily from $72m^2$ on a column in the past in reaching up to $1000m^2$ at the moment (Fig. 1). The corrugated sheets had to be adapted to the new requirements and the cross section evolved so that it could be better fitted to cover larger spans.

The façade and roof envelopes for single-storey buildings are erected from either corrugated steel sheets or sandwich panels. It has been recognized that by considering the cladding into static and dynamic calculations, the structure performs closer to real life behavior. Despite the fact that the steel consumption represented by the cladding is significant, it is mostly omitted in structural design.

The roof for single-storey structures in particular is built in the vast majority of cases using corrugated steel sheets. This has basically became a standard construction detail for single-storey buildings (Fig. 2). As it was mentioned before, the need for large openings followed-up the adaptation of corrugated sheets for larger openings. In Fig. 3 is presented the evolution of corrugated sheet sections. Corrugated sheets used to be considered to serve only as a support for thermal and hydro insulation. The trend now is to use the corrugated sheets not only as support, but also as structural elements.

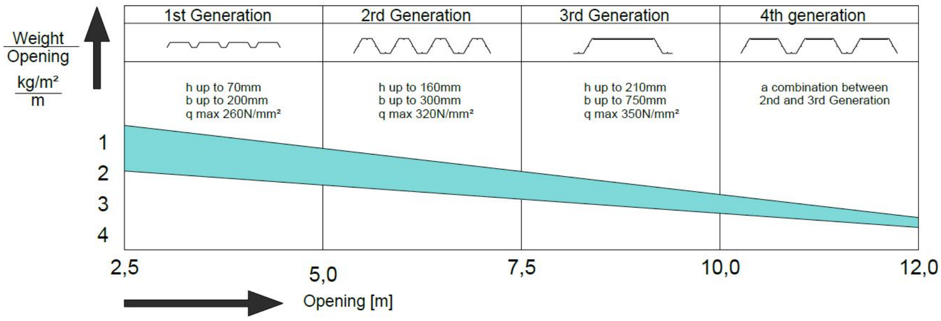


Fig. 3 – Corrugated sheets evolution trough time.

2. State-of-the-Art of the Research in the Field

The history of corrugated steel sheets began in the 1820s when it was invented by the British engineer and architect Henry Robinson Palmer who was also one of the co-founders of the Institution of Civil Engineers in 1818 (Bridgwood & Lennie, 2009). Working at the London Dock, he was given the task to solve the problem of roofing for the new warehouses that had to be built. The solution he presented was a light-weight corrugated iron sheet that made the layer more rigid leading to less framing to be required to support it as a roofing material. The first corrugated sheets were made from wrought iron using manual corrugated iron rollers (Fig. 4).

The patent was later sold to a carpenter, Richard Walker, who was a contractor in the New Docks. The Turpentine Shed, built around 1830, was the first building to be roofed with iron sheets pressed through fluted rollers. After the patent ran out in 1843, competition flooded the market with new products and corrugated sheets became a world wide dialect. The material was very popular and even the Queen’s consort, Prince Albert, ordered a corrugated iron ballroom for the Balmoral Estate that still stands, now a joiner’s workshop, and probably the oldest metal sheet building in existence (Thomson & Banfill, 2005).

The corrugated sheets soon crossed the Atlantic, starting to gain the industry interest almost at the same time as in Europe. In North America, the use of corrugated sheets were at first mostly experimental and limited to a few basic structures.

Fig. 4 – Early manual corrugated iron rollers, Kapunda museum left, Powerhouse Museum on the right).

During the California Gold Rush in 1849, a roofer from New York named Peter Naylor started a business that promised "portable iron houses for California" with most of the parts probably made from corrugated sheets that he used in practice. The advertised he promoted said that the 20 × 15 (foot) home was made from separate parts that could slide together, leading to building the house in less than a day. The price of this houses was cheaper than the ones made from wood and they were fireproof and more comfortable than a tent.

Fig. 5 – "House of Tomorrow", Howard Fischer, Chicago World's Fair, 1933 (Allen, 2006).

In the 1920-1930, in the United States, acceptance of cold-formed steel as a construction material was still limited, mainly because of the lack of an adequate design and a real interest in the material on behalf of the building codes.

In 1933, US architect Howard T. The Fisher proposed a family home made entirely of cold-formed profiles (Fig. 5). Although it benefited from positive publicity in the media of those times, the construction company that engaged in the construction of the new future-houses went shortly bankrupt due to a lack of orders.

The population was still reserved in constructing their homes with the new material. One of the motives one could invoke had to be related to the fact that cold-formed structures were still new on the market, with a short history and unpredictable in the long term (Allen, 2006).

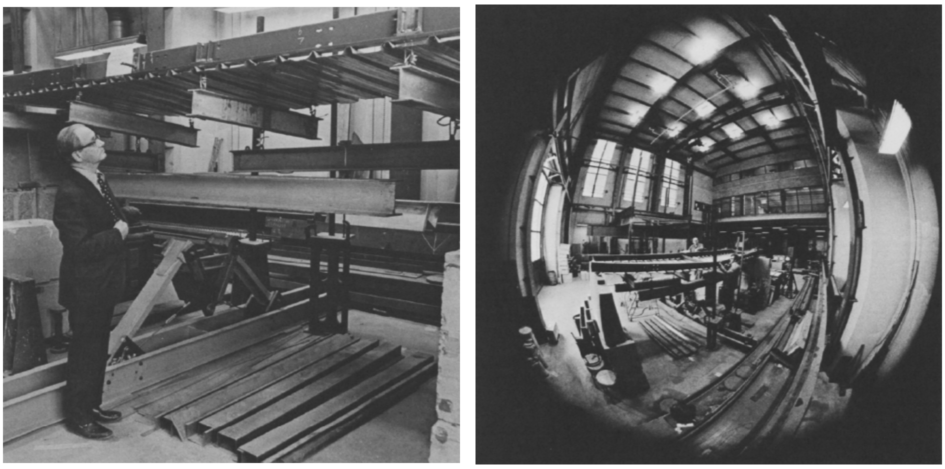


Fig 6. – George Winter at Cornell University on the left
Large scale testing in Thurston Hall Test Bay on the right (Winter et al 1972).

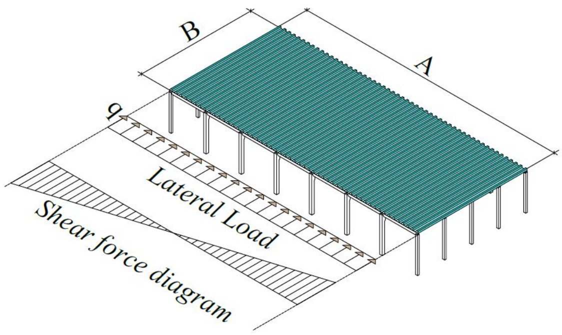
Following the World War II the military capacity was converted to domestic use. The abundance of steel in the modern era had increased the production capacity of steel mills in the United States and through the American Iron and Steel Institute (AISI) the focus was to invest in new steel research fields.

The task associated with cold-formed steel structures was given to George Winter from Cornell University (Fig. 6). He had to create specifications for cold-formed steel structural members that the engineering community could use. In 1946 the results of the intensive research culminated with "*AISI Specification for the Design of Light Gage Steel Structural Members*" (AISI

1946), which was subsequently adopted by building codes and soon become the governing standard for cold-formed structural members used even today in the USA. (Madsen *et al*., 2016)

George Winter's successor is Arthur H. Nilsson and he is one of the first to study the diaphragm action of the corrugated sheets. In cooperation with George Winter they started a systematic research on the corrugated steel sheets structural behavior. Their approach on the manner was a very practical one, because the extensive study aimed at providing specific answers for each type of corrugated sheet plates that existed at the time in the American steel industry catalogues. The study was purely experimental at first, and it has shown the many factors that influence the behavior of the diaphragm panel, stressing the importance of the fasteners and recommending welding techniques. The results obtained were presented as a design guide in which was given the allowable resistances and deflection for shear.

Larry D. Lutrell, also a Cornell University researcher continued the studies conducted by Arthur Nilson but at a larger scale. The results of the studies were printed in a document called the SDI "*Steel Design Institute Diaphragm Design Manual*" that was first published in 1981 (Lutrell, 1981). It is still in use today with the later revised edition published recently in 2016. In Fig. 7 is presented an interpretation given by the SDI on how the roof made from corrugated steel sheets acts as a diaphragm and its reaction to lateral load. Expression of deflection is also given.



$\Delta_{total} = \Delta_b + \Delta_s$
Δ_b = bending deflection
Δ_s = shear deflection

Fig. 7 – Diaphragm action according to SDI (Lutrell, 1981).

The corrugated sheets, if proper attached to the structure, acts as a bracing element. The diaphragm action has two major calculation envisioning.

The first one was discussed above, representing the American approach considering best to test individual real-scale sheet panels with independent results for each panel. The experience that the USA companies gained have been adopted in Europe thanks to the fact that they expanded their production in the old continent following the Word War II.

The main organization in Europe involved in the study of corrugated sheet acting as a diaphragm is the ECCS (European Convention for Construction Steelwork) enacted by Rolf Baehre and Otto Steinhardt. The scope of this institution is to promote steel in construction through the development of standards and information.

In Europe the diaphragm effect of the corrugated sheets was named "stressed skin action design" by professor Bryan E.R. from the University of Salford, England and the idea on which it marches differs totally from the American solution. In Europe the study focused on a more general perspective. The scope was the engineers to have sufficient data conducting the computation for any type of diaphragm setup. The method considers the flexibility *c* of a panel as a sum of partial flexibilities. The partial flexibilities have formulas based on the corrugated sheet cross section, fasteners and construction method.

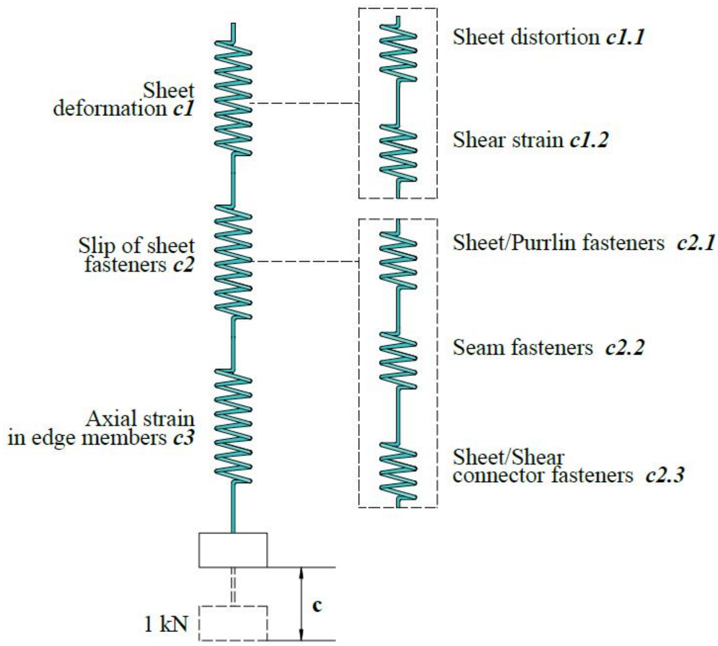


Fig 8. – Spring analogy for shear flexibility (Bryan, 1975).

In 1973 Bryan E.R. published the first European book that discussed the diaphragm action of corrugated sheets "*The stressed skin design of steel buildings*" (Bryan, 1973). The document is considered of great importance in the field. Rolf Baehre, as Chairman of the ECCS TC17 "Cold-formed thinwalled structures" recruits Bryan E.R. and his assistant J. M. Davies to prepare the first version of "*European recommendations for the stressed skin design of steel structures*" (ECCS, 1997). Printed in 1977, it would become the European standard for the design of the corrugated sheets. Thanks to this European recommendations, engineers had been given guidelines on how to consider building response in regarding strength and stiffness considering the stressed skin action in structural design.

In 1982 J.M. Davies published "*Manual of stressed skin design*" adding more information that would complete the European guide. Since Davies printed his book in 1982, no significant changes in the structure of the European recommendations had been undertaken. The latest version dates from 1995 but there is an interest in updating the European standard for stressed skin design that is expected to be presented in the near future.

3. Conclusions

Corrugated steel sheets captivated the interest of industry companies and research studies soon had to be carried to offer answers for the way this new construction material should be considered. Corrugated sheets provided the construction companies with a light material, easy to transport, deposit and work with that could cover large spans and at the same time presenting a pleasant architectural aesthetic design. It was observed that the sheets could be incorporated in structural calculations if provided with proper fastening leading to transforming the corrugated sheets in load bearing element in the structure.

There have been developed two ways on how to calculate the contribution of the corrugated sheets: using empirical formulation like the approached perfected in the United States and the second method is by considering the flexibility of the diaphragm as a sum of partial flexibilities, as done in Europe. Different countries are considering the diaphragm effect in their national design codes, but in the end they are an adaptation of one of the two methods mentioned before.

Corrugated steel sheets are currently used in structural design due to the strength and stiffness it brings to the structure. The main focus of the design guides are based on steel structures but for precast concrete structures the approach of construction is the same making it an interesting new field of study.

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STADIUL ACTUAL PRIVIND EFECTUL DE DIAFRAGMĂ CONFERIT DE TABLA CUTATĂ STRUCTURILOR TIP HALĂ PARTER

(Rezumat)

În prezent, există o cerere crescândă pentru clădiri tip hală parter, ca urmare a beneficiilor pe care acestea le aduc în ceea ce priveşte posibilitatea de realizare a spațiilor mari şi deschise, făcându-le astfel potrivite pentru activități socio-economice, culturale sau industriale. În ceea ce priveşte modul de execuție a închideri perimetrale şi a învelitorii acoperişului, pentru aceste structuri, tabla cutată sau panourile sandwich sunt cele mai folosite soluții. În ultimele decenii s-au efectuat multe cercetări şi studii îndreptate asupra utilizării tablelor cutate ca element de rezistență pentru structură. S-a stabilit faptul că prin încorporarea învelitorii şi a închiderilor perimetrale structura devine mai rigidă şi mai rezistentă. Prin luarea în considerare în calcul a învelitorii din tablă cutată, inginerul structurist poate anticipa mai bine comportamentul real al clădirii. Închiderile perimetrale devin foarte eficiente ca diafragmă de forfecare iar dacă se realizează o fixare corespunzătoare a tablei de cadru acestea pot fi considerate ca element participant în structură. În această privință, literatura de specialitate oferă teste la scară reală, care sunt demonstrate şi de experiența de pe şantier.