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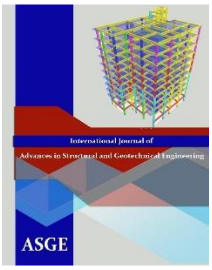

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Representation of Screw Connections for Sheathing Boards in Light Weight Structures

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ABSTRACT:

In this study, experimental and numerical investigations are conducted to characterise the screw behaviour in the connection between cold formed section and different sheathing boards alternatives. The investigated sheathing board alternatives include Steel sheets, Fibre-cement boards and Gypsum boards, which are typically used as cladding for the cold formed elements in light weight structures. Different types of screws are considered such as Hex Washer Head, Pan Head and Flat Head. A comparison regarding the modes of failure and shear capacity is stated. Additionally, the same connections are a represented numerically using finite element model, which is verified against the experimental test results. The connection representation showed close behaviour and failure modes compared to the experimental results. In this study, the numerical model approach is elaborated, which will be used as a component of another research program including testing full scale light steel panel subjected to cyclic loading.

INTRODUCTION:

The rapid improvement in the construction needs has motivated the research for new material and construction techniques that are more practical in terms of cost-efficiency and construction duration. Recently, light steel frame system (LSF) is becoming a popular replacement for traditional building systems, which in turn requires several researches in order to identify its behavior. LSF is composed of Cold-formed steel (CFS) elements, that provide the advantage of lightweight and the superior ease of construction compared to alternative materials such as concrete, timber and heavy steel systems. LSF system is becoming common for conventional medium and low high buildings and also for industrial storages and firms in many countries. Cold-formed steel elements are utilized in this system because of being non-combustible, insects proof, high-durable, lightweight and 100% recyclable. In addition, CFS provides high mechanical properties and advanced galvanization technology paint. The seismic behavior of LSF is one of the main areas of research in this system due to the complexity of CFS member combined with the sheathing board. However, the behavior of CFS shear walls subjected to lateral loads due to earthquake is not fully understood. In the last few years, many researches have been performed to study the behavior of light steel framed structure building. The major of these researches focused on the experimental and numerical investigation of the seismic response of wall panels. The shear wall cold-formed panel composed of CFS framing elements and sheathing boards. The steel frame constructed of top and bottom tracks connected with vertical stud members. The common section used for the studs (chords) is C lipped section while tracks are selected as U shape cold formed sections. The sheathing board is the main factor providing shear stiffness for the CFS shear wall panel. Plywood boards, steel sheets, fiber cement board and gypsum board are attached to CFS walls. The wall is anchored to the ground by means of connecting bottom track bottom track to the rigid supported ground beam of floor slab.

Also, the other practical alternative for providing shear stiffness is using an X strap bracing. The strap bracing act like traditional concentric bracing which transmitted lateral loads from the top roof level to the bottom floor levels to the ground foundation. In addition to the strap section, several elements contribute to the overall strength, ductility and stiffness of the lateral load resisting system as the connection between straps, the presence of gusset plates, the hold down element and the connected anchor bolts. In addition, CFS walls practically sheathed by various types of boards which can structurally name shear walls and it can be used as main structural elements, which act against horizontal loads.
The aim of the investigation is the development of computational models of shear walls based on the fundamental fastener response similar to the work presented in literature ([3–7]). This is achieved through performing laboratory tests on the connection between the steel element and several types of board. Afterwards, finite elements models are developed aiming to mimic the output behaviour of those tests. Moreover, this investigation will enable a mechanics-based method for performing the lateral response of any sheathed cold-formed steel system: shear wall, diaphragm, etc. in case where testing is not practical or available. Nithyadharan and Kalyanaraman [8,9], Fiorino et al. [10,11,12],Serretteet al. [13] and Okasha [14] experimentally determined the cyclic performance of these cold-formed steel to sheathing connections, while Vieira and Schafer [15] successfully characterized the monotonic behaviour of the connection between the wood boards and CFS steel frame. Fülöp and Dubina [16, 17] ultimately applied a tri-linear model to their shear wall cyclic results with some success, but did not attempt a complete nonlinear characterization. These all investigations were a part of large general projects of investigating the behaviour of shear cold-formed wall. This clarifies the importance of our screw connection tests and simulation numerical models for understanding the behavior of the cold-formed shear wall panels.

1. EXPERIMENTAL INVESTIGATION:

1.1. General

Series of shear plate connection tests were carried out to evaluate the shear behaviour of self-drilling screws connecting different elements. The experiments are conducted on three different connections. The first type of connections is screwed steel to steel connection representing the connection between the framing elements of the CFS wall and the connection between the CFS elements to the steel sheathing boards. The second type of connection is screwed steel to fibre cement board connection, which represents the connection between the CFS framing elements and the FCB sheathed panel. The third type of connections is used between the steel frame and the gypsum sheathing board. Three specimens from each type of connection were tested according to European Convention for Constructional Steelwork code ECCS code [1]. The test is simplified by applying tension force on the two plates connected by one screw as shown in Figure 1. The applied tension force on the plates results in direct shear on the screw. The relationship between the applied load and the displacement between the two plates were measured. A comparison between the three types of connections is established.

(a) Case of steel to steel connections **(b) Case of steel to sheathing connections**

Figure 1 The test configuration for the sheathing connected to steel element.

1.2. Type of the tested screws:

The experimental test was conducted on three types of screws are summarized as follows:

1- Hex washer head with screw type No.25:
Screw with nominal diameter 4.8 mm and head diameter equals 9.3 mm with screw length equals to 30 mm. It is used at the joints between the steel framing members in the free side. Also, this type of screws is used to connect the diagonal straps to the framing elements.

2- Combined drive and pan head with screw type No.25:
Screw with nominal diameter 4.4 mm with head diameter equals 10.53 mm and screw length equals 25 mm. It is used at the connections between framing elements of the CFS wall at the sheathed side.

3- Flat head with screw type No.25:
Screw with nominal diameter 3.81mm with head diameter equals 9.3mm and screw length equals 55mm. It can be used to connect the sheathed board with the steel framing members.

1.3. Test description

All dimensions of tested specimens are constructed in accordance with the European standards, ECCS [1]. Regarding the first type of connection - steel to steel connection - three specimens of two steel plates of dimensions 300x50x1.2 mm are connected with self-drilling screw as shown in Figure . The end distance of the screw was 30mm. The two sheets were placed on the tensile test machine GALDABINI [19] test machine 100 ton capacity load. The tensile machine has two clips in which the tension force is applied at one end while the other is being fixed to the base of the machine. As a result of applying tension force on the upper plate, shear force is induced in the screw as the upper plate is tensioned upward by means of machine clip. Tension force and relative displacement was measured by mean of machine load cell.

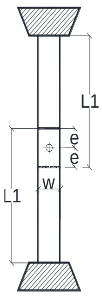


Figure 2 Steel to Steel sheets specimen

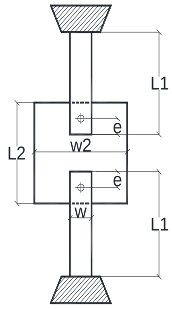


Figure 3 Steel to board specimen

12 specimens were tested including 6 for steel to steel sheets -2 specimens for each type of screw-, 3 steel to cement boards and 3 for steel to gypsum board. As shown in Figure two steel plates 300x50x1.2 mm were used to fix the sample in the machine grape and in between the sheathed plate 300x300x12 mm. The steel plates were connected with the sheathed material with two screws at the ends of sheathed plate. The end distance of the screw was selected 30mm. This setup was suggested to prevent the failure of sheathed tested plate due to grapping force of machine. Table (1) indicates the geometric configuration of the tested specimens.

1.4. Applied load

Tension GALDABINI [19] test machine 100 ton capacity load was used to test the specimens. The machine has two clamps at which the steel plates are attached with special grips to prevente any slipage of the samples as shown in Figure .

Table 1 Geometric configuration of the tested specimens for the different sheathing types

Connection type	W1 (mm)	W2 (mm)	L1 (mm)	L2 (mm)	e (mm)
Steel to steel	50	-	300	-	30
FCB to steel	50	300	300	300	30
GB to steel	50	300	300	300	30

The tension load was applied at the upper grip of machine gradually until reaching the failure load of specimen. The load cell is used to measure the load value. The relationship between the applied tension load and the displacement between the two plates of the specimen were measured by data acquisition system attached with the machine and the data recorded in a digital file. The mode of failure of each specimen was observed. A comparison between the failure behaviour of each connection type was developed.

Figure 4 the machine used in testing the screw connection

2. RESULT AND DISCUSSION:

2.1. Results of Steel to steel connection type

Regarding the steel to steel type of connection, Figure indicates the load displacement relationship of the three different screw head connecting steel plates. Average results are used to compare between the different behaviour of the three head types.

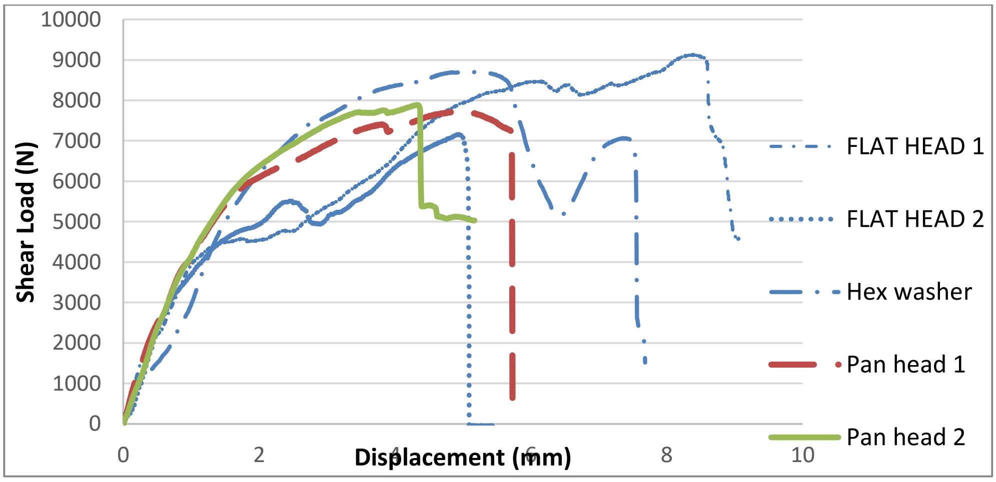


Figure 5 Load-displacement relationship of steel to steel screwed connection.

The investigation of Figure indicates that the ultimate shear capacity of the hex washer head screw is higher than the combined pan & drive head screws and the flat head type. This is due to the slightly bigger diameter of the hex washer screw than the combined pan head & Flat head screw. Another observation can be notice that Hex washer head gives more ductility and deformations than combined pan & drive head and flat head. The decrease in load during failure is smoother than the sharp fall in the flat head and combined pan & drive head curve which represents that the failure is suddenly occurred.

2.1.1. Mode of failure

According to the observation of the modes of failure, the following can be noticed:

- In case of combined pan & drive head the failure wasn't located in the screw thread. At the failure shear load the head of the bolt was pulled out away from the screw body and the screw head slipped out of the connection. This explained the failure plateau represented in the load-displacement relation curve as shown in Figure 6.
- In case of hex washer head pure shear failure for the screw was observed without much bearing effect in the steel plate. This also support the previous explanation for the increase of the ultimate shear strength of the hex washer over the combined pan and flat head as shown in Figure 6.
- In case of Flat head screw, shear failure was founded in the threaded area of the screw. So, the shear capacity of the shear connection mainly depends on the shear capacity of the screw connected the two plates as shown in Figure 6.

Figure 6 Modes of failure of three types of screws

2. Results of Steel to fibre cement board connection type

Regarding second type of connection - fibre-cement board to steel connection, Figure explains the load displacement relationship of steel plate to fibre cement board. The type of screw was Flat head screw. The chart includes three specimen results.

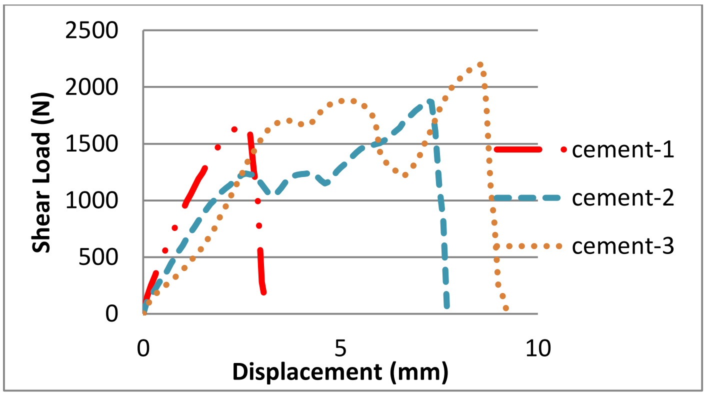


Figure 7 Load- displacement relationship of steel to fiber cement board connection.

The observation of Figure indicates that ultimate load of the three specimens are approximately the same but the displacement is different, which can be explained by the nonhomogeneous composition of the board material.

2.2.1. Failure mode

The investigation of the failure mode as shown in Figure indicates that the failure started by a crack initiation through the weak cross section of the FCB. While increasing the load, the crack propagates along the weak path across the FCB. So the crack tends to find its path across the weak section of the FCB which varies from one specimen to another due to the nonhomogeneous composition of the fibre cement boards. When the load exceed the ultimate tension capacity of the cement board the weak section including the screw opening start to break.

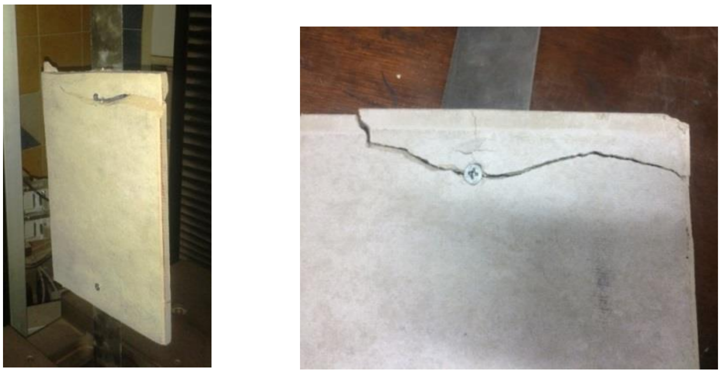


Figure 8 FCB test configuration and failure modes during shear loading test

2.3. Results of Steel to gypsum board connection type

The results of shear test on gypsum board to steel connection are illustrated in Figure . The type of the screw was flat head screw. The chart includes results for the three specimens. The study of this chart indicates that:

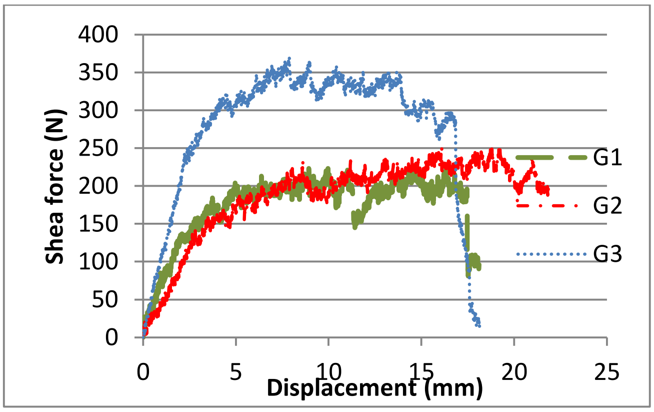
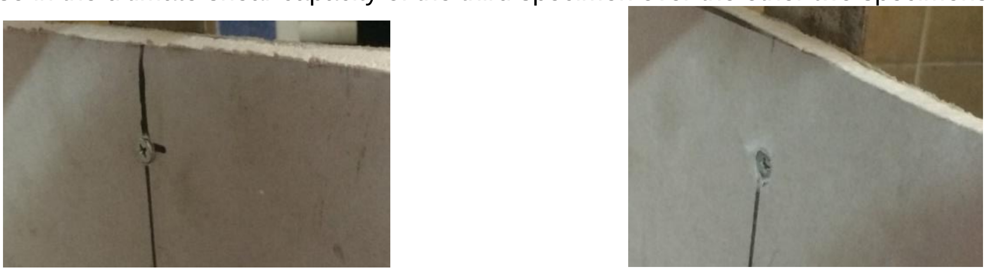


Figure 9 Load – displacement relationship for Gypsum boards to Steel Connection

The first and second specimens gave approximately the same ultimate strength. Third specimen gave a larger resistance than the first two specimens. This variation comes from the way of the fixation of the screw within the gypsum board and this will be discussed in the failure mode observation.

2.3.1. Failure mode

As shown in Figure 1, bearing failure of the gypsum board was observed during the test. Screw pull out due to the bearing failure in the gypsum board occurred. The dominant mode of failure of this connection is a combination of bearing in gypsum board and screw pull out failure. So, the self-drilling operation quality has a significant impact on the ultimate shear strength. If the screw is well tightened but the screw deeply penetrates the gypsum board through tightening operation as shown in Figure 10b the screw might easily slipped from the gypsum board. While if the screw is not allowed to deeply penetrate the gypsum board through tightening as shown in Figure 10a, the pull out resistance of the screw is increased. This observation also explains the increase in the ultimate shear capacity of the third specimen over the other two specimens.



(a) (b)

Figure 1 the impact of screw installation and tightness on the gypsum board panel before load application

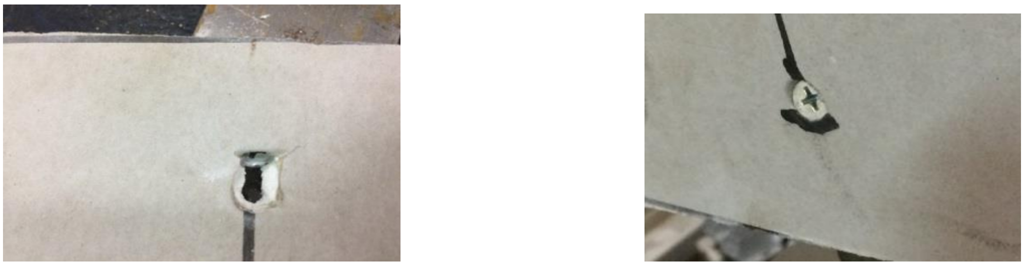


Figure 2 Gypsum board bearing mode of failure

A Comparison between cement board, gypsum board and steel plates screwed connection to steel plates is shown in table 5. The values listed in the table represent the average results of the different specimens. The table summarizes the ultimate shear strength of each board type against the deformation of the connection at the ultimate load and the final deformation at failure

Table 5 Comparison between the test results of connections for different board levels

Connection type	(avg.)Ultimate shear strength (KN)	ΔUltimate (mm)	ΔFinal (mm)
Steel to steel	8.04	6.67	8.45
Gypsum Board to steel	0.28	12.35	71.76
Cement Board to steel	1.94	6.62	8.65

As shown in table 5 the ultimate shear strength of steel to steel connection is more than shear resistance that of other two types of boards. While, the cement board gives more shear resistance than gypsum board to steel connection. These results can be explained by observing modes of failure of each connection.

- In case of steel to steel connections, screw shear failure was observed in the connection without a remarkable bearing in steel plate. It can be concluded that, the shear capacity of the connection is governed mainly by the shear strength of the screw connecting the two plates as shown in Figure 3.

- In the case of gypsum board to steel plate connection, bearing failure in gypsum board was observed. As the load increased the screw start to slip and pull out from the gypsum board. As a result of that, the gypsum board to steel connection shear capacity is governed by the bearing capacity of the gypsum board. Also, the surface contact area of the screw head affects the shear capacity of the connection. As the screw head has bigger area contacting the gypsum board surface or using a washer to increase the contact surface the shear capacity will increase. It was noticed from the test results that when flat head screw was used the bearing resistance of the connection decreased as shown in **Error! Reference source not found.**.
- In the case of Fibre cement board no bearing or slippage was observed in the board. The element failed due to the shear failure of the fibre-cement board itself and not the connection as shown in **Error! Reference source not found.**. The different tested specimens showed that failure was observed across the weak section including the screw hole in the board.

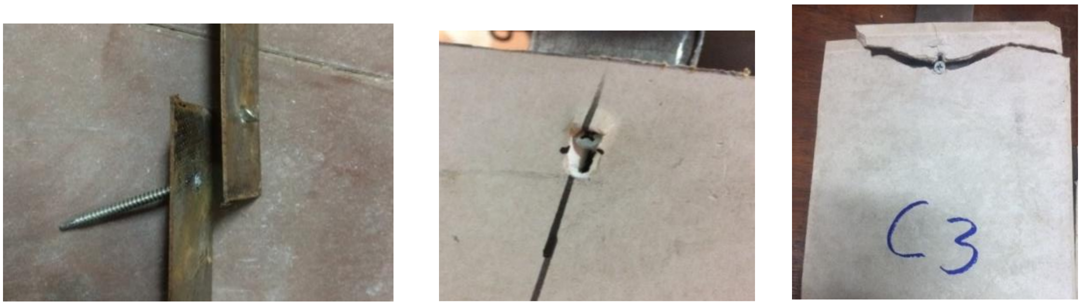


Figure 3 Modes of failure in the three screw connections in Steel, Cement and Gypsum board

3. NUMERICAL INVESTIGATION

3.1. Introduction:

Where the screw is an important factor in cold-formed shear wall behavior, the simulation of screw is a critical factor in numerical modeling of CFS sheathed wall. Hence, the modeling of one screw in a simple form between two plates or three plates is suitable way to understand the behavior of screw model. The different representation methods of screw in Abaqus software are evaluated to verify the previous experimental test of screw connections in finite element model. The objective of this study is to verify the screw modeling approach to be used in developing the CFS shear wall model. Furthermore, the ability to perform an adequate numerical model for the connections allows the studying of different parameters in cold-formed steel sheathed panel to resist the lateral load.. The commercial available software package ABAQUS, version 6.14-4 [2] is used to conduct numerical models.

3.2. Numerical model layout:

Two cases are performed to simulate the screws connection. The first case represents a connection between two plates as shown in figure 13. This case can be found in light weight systems in different elements such as end/interior stud to top/bottom track connection, noggin to stud connection and also the connection between cement board and framing elements. The second case represents a connection between three plates as shown in **Error! Reference source not found.**. Such case can be found in the corner connection that attaches the cement board to both top/bottom tracks

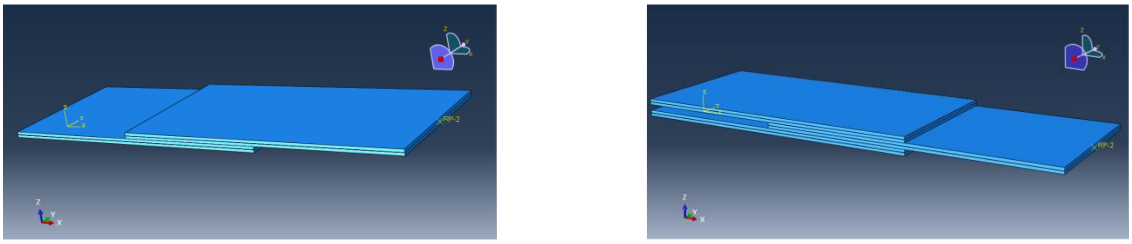


Figure 13 Model configuration for two and three connected

The screw can be modeled by mesh independent fasteners. Mesh-independent fastener is a suitable method to define the connection between point-to-points on two or more surfaces. The fastener can be placed anywhere between the parts that are to be connected regardless of the mesh. Therefore, the location of the fastener can be independent of the location of the nodes on the surfaces to be connected. Each layer connects two fastening points using connector element [2]. Two definitions of the fasteners behavior are studied in this section; the first definition is to assume that the screw will behave as nonlinear elastic element. The non-linear element is defined through introducing certain values that represents the shear behavior the P-Δ curve. Those values can be determined using previous studies or experiments similar to the one described in this study. The second approach to define the connection is to assume that the fastener starts behaving as a linear elastic element for a short region then it behaves with plastic properties. This approach as well can be implemented in the numerical model though P-Δ curve.

3.3. Elements:

The element assembly is composed of two/three instances of one part modeling the plate element. Cold-formed steel plates and sheathing are modeled as four-node shell finite elements S4R. This element has three translational and three rotational degrees of freedom at each node. The element considers finite membrane strains and large rotations. Therefore, it is adequately conformed for large-strain analyses and nonlinear geometry problems. [2].
This type of element uses linear shape functions and has reduced integration scheme to prevent shear blocking in coarse mesh. Five integration points are utilized through the thickness of the element. The mesh size of the steel plates is selected 5x5 mm. fine mesh can represent all buckling modes including local, distortional, and global with reasonable accuracy [18].

3.4. Material properties:

The cold-formed steel is modeled as isotropic elastic material with Young's modulus E= 2E5 MPa, Poisson's ratio v= 0.3 and yield stress= 360 MPa. The value for Young's modulus is commonly used in the computational modeling of cold-formed steel. According to Abaqus analysis user's guide, this type of material is adequate since elastic strains are expected to be small (less than 5%). Also for simplification the steel material stress strain curve is defined with two portions the elastic plateau and yielding plateau. The sheathing material, fiber cement board is modeled as isotropic elastic material with Young's modulus E=2E8 MPa and Poisson's ratio v= 0.3 to minimize diaphragm deformations and represent it as a rigid body diaphragm.

3.5. Boundary Conditions:

The boundary condition defined in the model is guided by the ones utilized in the test setup described earlier. The edge of one of the two plates is totally restrained from displacement and rotations which simulate the end of the plate which was attached to the fixed bottom clip of the testing machine. Regarding the three connected plates model, two plates are totally restrained from the edge and only the loaded plate is allowed to move in the direction of the load. All side edges for plates are restrained also from all degrees of freedom except the displacement in the longitudinal direction – direction of tension force- to prevent any out of plane deformations or rotations. indicate the boundary condition in the cases of study.

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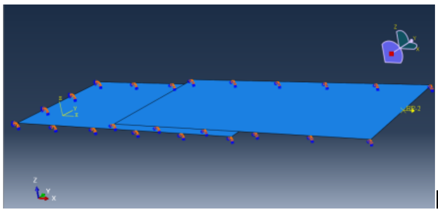

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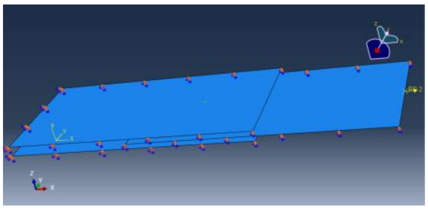


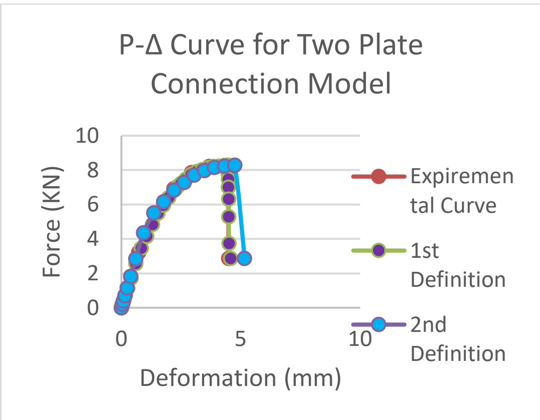
Figure 14 Two and three plates model edges constrains

To simulate the free end of the plate connected to the other clamp of the machine all the nodes at the edge of the plate are constrained by MPC beam constrain to reference point 2 (RP2) in order to prevent deferential deformation along the edge of the plate as show in Figure 27. This constrain also simulate the reality that the plate end in the experiment is attached to the machine clip so all the points at the edge will be tensioned in the experiment. Machine applied tension force can be modelled in ABAQUS by two approaches. The first is to assign line load along the edge of the plate. However, this procedure will not allow to easily produce P-Δ curve as the load will be distributed along all the nodes of the edge. So, it will require to perform summation for the reactions at each node along the plate edge in order to determine the total tension force. The second approach is to apply a concentrated force at the RP2 as previously described, which will facilitate extracting the data such as the reaction force and deformation at this point from the model. So, the second procedure is adopted in the modeling.

3.6. Step configuration:

Step for numerical solution is defined as Static Riks method with nonlinear geometry which represent force loading protocol used in the experiment. In static Riks approach the load will incrementally increase until failure occurs. Afterwards it continues after failure to represent the forces and deformation values after failure to completely represent P-Δ curve after ultimate load capacity.

3.6. Result and Discussion:



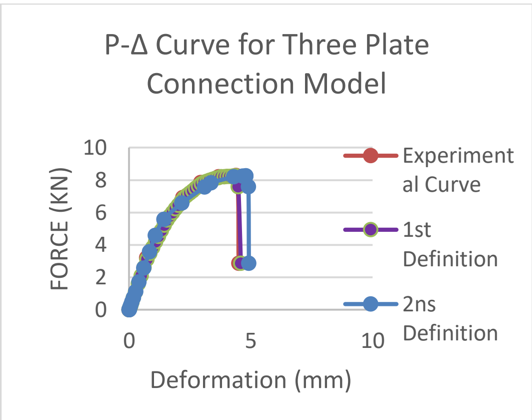
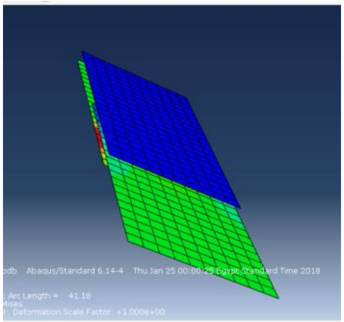
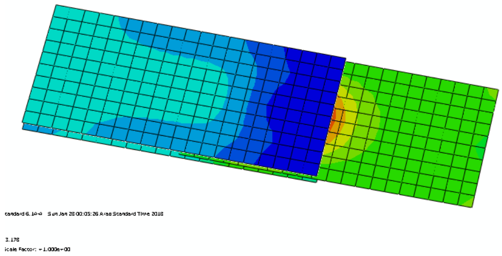


Figure 15 Load – displacement relationship for Two plates Connection Model **Figure 4 Load – Displacement relationship for Three plates Connection Model**

According to the previous model description, the results shown in Figure are developed. The P-Δ curves for the elements are established according to the two definition approach previously stated. The two approaches resulted in good agreement with the experimental results. Accordingly any of them can be adopted in the analysis.



a) Case 1 of definition



b) case 2 of definition

Figure 5 Stress distribution results in lower plate.

Regarding the three plates model, P-Δ curves resulted from the numerical models also match the experimental output curves. However, the second definition will be adopted in representation for the three plates screw connection because according to plate stress diagram it was found that the stress induced in the third plate is very small values almost zero stress as shown in Figure 5 which means that the third plate doesn't adequately attached by the fastener. On the other hand, stress distribution diagram shows more reliable stress values on the third plate which means good convergence in the solution within the second definition. This conclusion also appears in connector force diagrams.

4. Conclusion:

In this study experimental and numerical investigations were performed to evaluate the steel to board connections in light weight steel. The experiment program included testing 12 specimens that represent different board material which are steel sheets, gybsum board and fiber-cement board. The specimens included as well testing different types of screw which are Flat head, Hex washer head and Pan Head. The outcome of this research can be summarized in the following points:

- Shear capacity of the screw connection significantly affected by screw head type
- The screw of hex washer head gave more than 10 % in shear resistance than the pan and flat head type
- The quality of self-drilling process and screws material has noticeable effect on the screw connection capacity.
- Screws shear capacity increases in the steel sheets by 75% than Cement board and more than 88% in case of Gypsum board panel
- The screw connection in case of Gypsum board affected by the bearing capacity of the board. So, using of washer plate or increasing the head size of the screw will affect the screw capacity. While in case of steel sheets and cement boards mainly affected by the shear capacity of the screw.
- Two types of numerical models were developed representing two and three plates.

- Mesh independent fastener with elastic plastic property definition is the most reliable simulation for screws in Abaqus Program. As the results were in consistence with the experimental results.

The outcome of this research can be used to better represent the impact of boards on the lateral resistance behavior of light weight steel panels, especially when subjected to seismic loads. A full scale wall panel was experimentally and numerically investigated by the authors in a different study according the results developed in this research.

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