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Monotonic Simulation of Fastener-Based Cold-Formed Steel Shear Walls

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Abstract — *Cold-formed steel (CFS) Shear wall has become popular in the construction industry because of some exceptional benefits like high strength to weight ratio, low maintenance, and high durability. Still, there is a crucial problem, particularly for promoting CFS structures in the seismic region, where many design elements stay open. The aim of this research is to analyze the lateral load capacities of shear walls used in residential buildings with CFS frames to overcome this problem. Five high-fidelity finite elements (FE) models for simulation of shear wall behavior with different types of sheathing materials, i.e., Fiber cement board, gypsum board as well as FE-CFS shear wall model without sheathing board, are presented in this paper. Shear walls were subjected to monotonic lateral load, and a comparative study of load-carrying capacities are presented. It was observed that the addition of sheathing to the CFS frame improves the shear resistance of the wall structure. Further study was carried out by simulating the shear wall models with varying the thickness of sheathing boards for observing its effect on the lateral load-carrying capacity. The main failure modes observed were screw pull-out, which caused sheathing material separation from the frame in some locations, and local buckling of studs. The results of this study (like various shear wall failure modes observed through Abaqus modeling) can be useful for practical considerations.*

Keywords — *ABAQUS CAE, FCB board, Sheathing, CFS Shear Wall, Monotonic Lateral Load*

I. INTRODUCTION

The application of Cold-formed steel (CFS) is significantly increasing because it is delivering a suitable solution to the need for low-cost, high-performance houses. There are numerous advantages of CFS, like the lightness of the arrangements, high quality of the end products, and adaptability provided by the wide variety of shapes and section dimensions. Furthermore, since CFS systems are used in dry constructions, they require a short execution period. CFS wall is the principal lateral load resisting element used in the seismic area as it is a better option considering the economy in handling and transportation, a high strength-to-weight ratio, and low maintenance for a long period of time. Wall systems consist of a CFS frame covered with sheathing boards for interior partitioning and exterior cladding. There are different kinds of sheathing boards like gypsum board, oriental standard board (OSB), Fiber cement board used in the entire wall system with sheathing board to provide lateral stability to the structure. CFS frame consists of studs made by two-lipped channel sections connected back-to-back and two tracks which is a single unlipped channel. Various components of the CFS wall are shown in Fig. 1. In CFS framework design, the seismic performance of the wall is affected due to the relation between the steel elements, sheathing boards, and their connections. A lot of research has been performed in the past to study the action of CFS sheathed walls of steel sheets, OSB, and plywood [1–3]. A similar kind of board is also considered by the “American Iron and Steel Institute” (AISI S213), where its shear strength is described tabularly and is limited to specific configurations [4]. Numerical, computational, and experimental investigations of Sheathed CFS shear walls revealed that both local fasteners, as well as global sheathing deformations, are equally critical for wall strengthening under compression loads [5–6]. A numerical study is carried out following FEMA P695 for Euro codes, in which the result is idealized by nonlinear models using static pushover as well as incremental dynamic analysis [7]. In order to determine the efficiency, different aspects, and accuracy of the numerical model of CFS shear walls, a comparative study has been conducted on both macro and micro categories [8]. To understand the seismic behavior, three distinct numerical models for CFS shear walls with gypsum sheathing were built and tested monotonically and cyclically as part of the ELISSA project [9]. The use of bamboo-based materials in CFS structures promoted them as potential eco-friendly and cost-effective building materials [10]. Advanced numerical modeling and non-linear analysis of steel frame members using linear, shell, and hybrid shell components have been extensively researched previously [10–12]. Sheathing modeling with shell elements [13] and membrane elements [14] was also studied extensively previously. In the past, various sheathing boards of CFS walls with diverse combinations were tested [15]. It was observed that Plywood considerably improves the shear capacity of CFS shear walls compared to the use of gypsum boards. The result of reducing the spacing among studs marginally improves the shear capacity of the CFS shear wall. The least safety factor of 2.0 is suggested for lightweight sheer panels in the design procedure. The impact of various thickness of boards, like gypsum board, OSB (oriented strand board), steel sheets, and plywood, was further compared to the effect of these kinds of sheathing boards on the rigidity of the structure [16–18]. Plywood sheathing was found to increase the shear strength by 10% of CFS shear walls as compared to OSB sheathing. The outcome of the screws which were connected to the sheathed boards and the steel frame components were closely monitored, and it was observed that there was a reduction in stud buckling as well as twisting deformation, which has improved the stiffness of the wall [18–20]. It was also observed that non-structural elements like plasterboard lining contributed to the lateral strength of the CFS frames [21].

This research will investigate the overall response of lateral loads on Fiber Cement Board (FCB) sheathed-CFS framed shear walls. The aim of the research is to implement an efficient fastener-based simulation of FCB-sheathed-CFS shear walls, using FE software of ABAQUS [22], and also validate the proposed computational model with previous experimental analysis. The primary goal of this research is to propose design guidelines for systems based on an overview of finite element modeling. This work proposes an improvement in CFS building capability as well as delivering key performance requirements for the final application of design codes.

II. MODELLING APPROACHES

Models implemented in this paper are various CFS shear walls under lateral load capacities. Configuration adopted herein is a work of Badr et al. [23], as illustrated in Fig. 1. This research entails the development of an experimental model using ABAQUS/Standard Version 6.14.1 [16] with the simulated shear wall of CFS studs tracks, fiber cement board, and gypsum sheathing at the exterior side of the wall. Table I displays the model parameters used in this paper. Herein, for all six finite element models, geometric limitations, residual stresses and strains are not involved. Important parameter of an FCB sheathed CFS shear wall is the CFS-to-FCB connection and how they are modeled using Abaqus Software.

III. TEST SPECIMEN

A. Model Geometry

Six shear wall models used in this research are made up of CFS having 1200 mm width and 2400 mm elevation. The Wall structure of the model, as shown in Fig. 1, is composed of a steel frame sheathed in FCB. Track members in this CFS frame consist of un-lipped channel sections with dimensions 102.4 × 50 × 1.2 mm, end studs made of double lipped channel section with dimension 100 × 50 × 10 × 1.2 mm attached back-to-back & mid-width intermediate stud made up of a single un-lipped channel. Cross-sectional details of stud and track are shown in Fig 2, and the elements are assembled together as illustrated in Fig 3. (a)-(b).

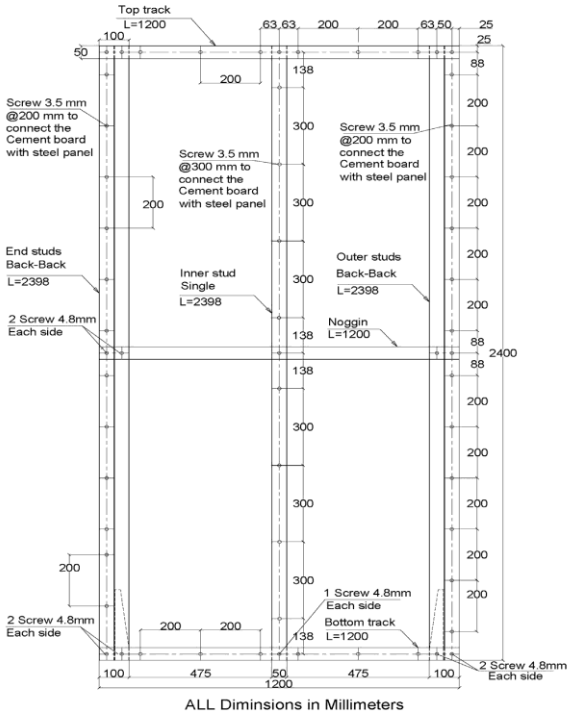


Fig. 1. Shear wall Detailing

[23]

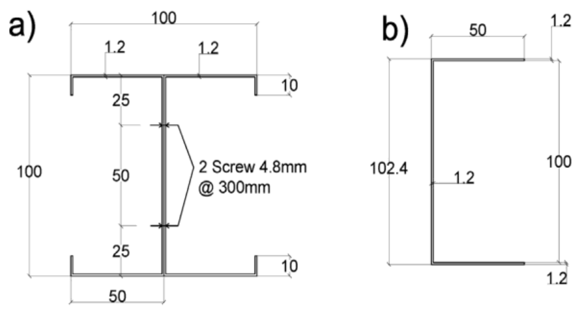


Fig. 2. Cross-section details of a) stud and b) track [23]

TABLE I
General Model Details

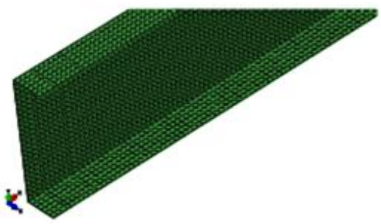
Element of Frame	Dimension (mm)
Stud (exterior)	Back-to-back Lipped Channel section 2400x100x50x10x1.2
Stud (Interior)	Single Unlipped Channel section 2400x100x50x1.2
Track	Single Unlipped Channel section 1200x102.4x50x1.2
FCB sheathing	Thickness: 8,12,16
Gypsum Sheathing	Thickness: 12,16

Fig. 3(a)Without Sheathing Fig. 3(b) With Sheathing

Fig.3. Assembly of Shear Wall

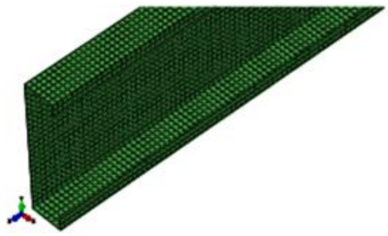
B. Element and Discretization of Meshes

Four noded shell finite elements (S4R) are used as mesh elements for channels as well as sheathing. Mesh density has an important impact on the performance of CFS members in FEA, according to previous studies [24]. A coarse mesh can capture distortional and global buckling modes but cannot replicate local buckling modes accurately. A medium or fine mesh, on the other hand, will accurately reflect all buckling modes, including local, distortional, and global modes. Furthermore, once a reasonable mesh is used, the response difference between different types of the element becomes minimal for these purposes; a relatively fine mesh is used in this modeling attempt, as shown in Fig. 4. For the model, steel members with a seed size of 5mm in real length and sheathing board with a seed size of 20mm were used.



a) track

b) sheathing board



c) stud

Fig. 4 Mesh formation of
a) track, b) sheathing board, and c) stud

C. Material Specifications

In this computational modeling of CFS, Young's modulus of E=2x10^5 N/mm^2 & Poisson's ratio (υ) of 0.3 is used. As per this ABAQUS user's manual, such material is suitable since elastic strains are expected to be small (less than 5 percent). Sheathing materials are shown to be isotropic elastic with Young's modulus E= 3000 N/mm^2 for FCB Sheathing and Poisson’s ratio (υ) as 0.3 and E as 2100 N/mm2 and 2272.1 N/mm^2 for gypsum sheathing of thickness 12mm and 16 mm respectively to minimize diaphragm deformations. The detailed specification of the Model is as tabulated in Table II.

TABLE II
Material Properties for Modeling

Material	Young's Modulus E Unit (N/mm^2)
Cold-formed steel Elements	2x10^5
FCB Sheathing	3000
Gypsum Sheathing 12 mm	2100
Gypsum Sheathing 16 mm	2272.1

D. Fastener connection

An important part of this modeling approach is connection behavior. There are two types of connection used (i) CFS-to-CFS connection and (ii) CFS-to-Sheathing board connection. The modeling of the CFS-to-CFS interaction is shown in Fig.5(a). Mesh independent fasteners were used to model the screw connections. The use of mesh-independent fasteners is an easy way to establish a point-to-point relationship between different surfaces. Rivets, spot welds, screws, bolts, as well as other fastening devices could be used to make these ties. The fastener’s position may be independent of the nodes on the surfaces to be connected. A connector function is used by each layer to join two fastening points.

CFS-to-CFS connections are modeled by Multi-point constraints (MPC) pinned from ABAQUS library. It is implemented to limit all translational degrees of freedom between the two nodes, but rotations are unaffected. This model includes three connector sections: screw for steel-to-steel interaction on the (i) open side (Hex washer) and on the (ii) cladded side (Pan Head), and (iii) a screw for interaction for steel to FCB connector. Sheathing-to-frame connections, i.e., the fasteners connecting the sheathing to the CFS frame, are modeled as board connectors using CONN3D2 connector element from the ABAQUS library, as shown in Fig. 5(b).

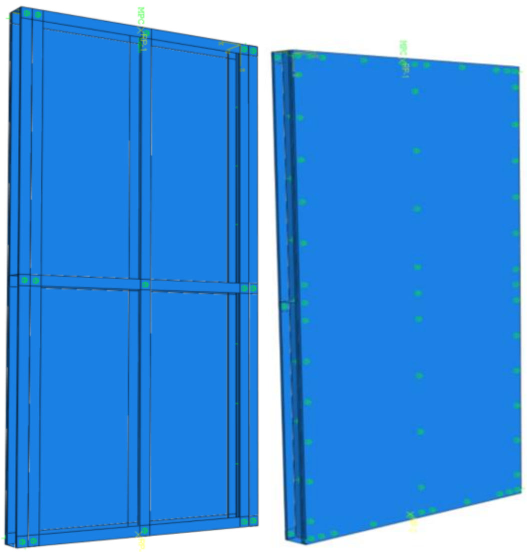


Fig.5 (a) **Fig.5(b)**

Fig.5(a) CFS-to-CFS Connection Detailing
Fig.5(b) CFS-to-Sheathing Connection Detailing

E. Boundary Condition and Loading

The top track's out-of-plane support was modeled as transverse roller constraints. Two lines of nodes on the top track's web are fixed in the transverse direction at the precise position of the screws connecting the top of the shear wall specimen to that of the structural member. The purpose of this constraint is to restrict the shear wall to in-plane movement.

In this model, the top of the CFS shear wall is subjected to a lateral monotonic load. As shown in Fig. 6. Using the RIGID BODY command in Abaqus, one end cross-section of the top track is connected to a reference node at its centroid.

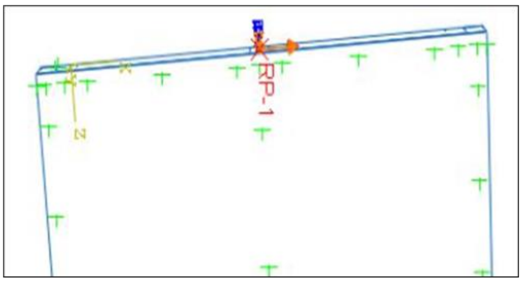


Fig.6. Loading Model

IV. EXPERIMENTAL VALIDATION AND FINITE ELEMENT MODEL

A sequence of six shells finite element models with good accuracy are initiated in ABAQUS to reproduce ten full-scale shear wall tests conducted [23] using the modeling protocol as presented here. The computational outcomes of the analyses of these developed models ate compared with different Sheathing material and thickness. The force-displacement response, peak load, and lateral deflection at peak load for each model compared with the experimental results, which gives an insight into the failure of frame-to-sheathing connections.

A. Force-Displacement Response

The force-displacement curve is showed in Fig. 9. (a)-(d) shows the response of the developed computational models. A summary of computational results, including peak load and the corresponding lateral displacement, is provided in Table III.

TABLE III
Computational result

Model	shear wall 2400 x 1200 mm Sheathing Material	Thick ness (mm)	Peak Load (kN)	Lateral Displacement (mm) at peak load
FCBM 8	Fiber Cement Board	8	63	54.82
FCBM 12	Fiber Cement Board	12	68.68	61.08
FCBM 16	Fiber Cement Board	16	70.64	52.91
GBM1 2	Gypsum Board	12	68.75	70.02
GBM1 6	Gypsum Board	16	70.41	61.59
CFSM	Without Board	-	23.65	58.11

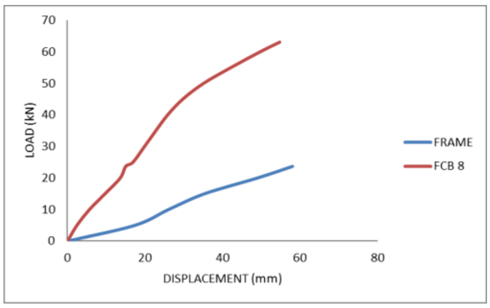


Fig. 9.a) With and Without Sheathing Board

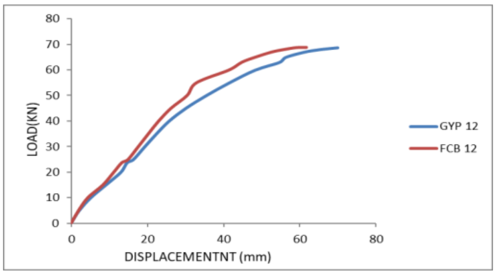


Fig. 9.b) FCB and Gypsum board having thickness 12 mm and 12 mm

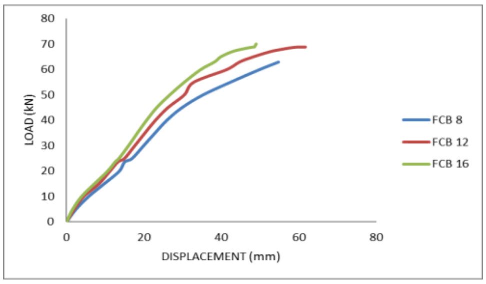


Fig. 9.c) FCB Sheathing having different thicknesses

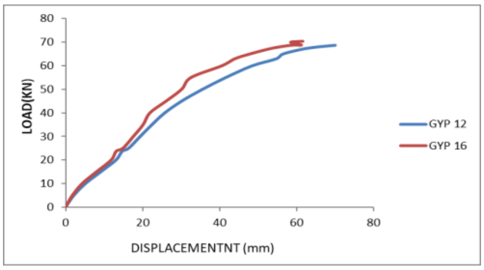


Fig. 9.d) Gypsum Sheathing having different thicknesses

Fig.9. Load vs. Displacement curve

B. Sheathing to Frame Connection Failure

The developed FE models allow the assessment of the manner in which shear force in the shear wall is distributed to the fasteners. In particular, Fig. 10 shows the deformed shape of Model FCBM16 at the end of the analysis with a focus on the deformation of the sheathing-to-frame fasteners. Response of fasteners on top track and chord studs on the right side is not shown in the figures due to the symmetry. Force in fasteners on chord studs and tracks at the corner reaches its peak when the overall shear wall specimen reaches its peak load at the lateral displacement of approximately 61.68mm.

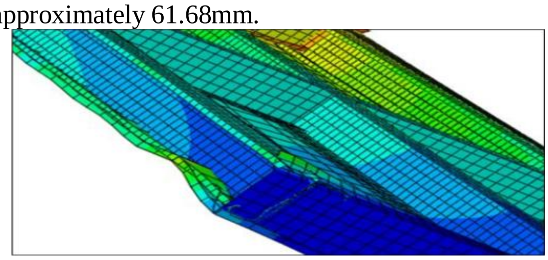
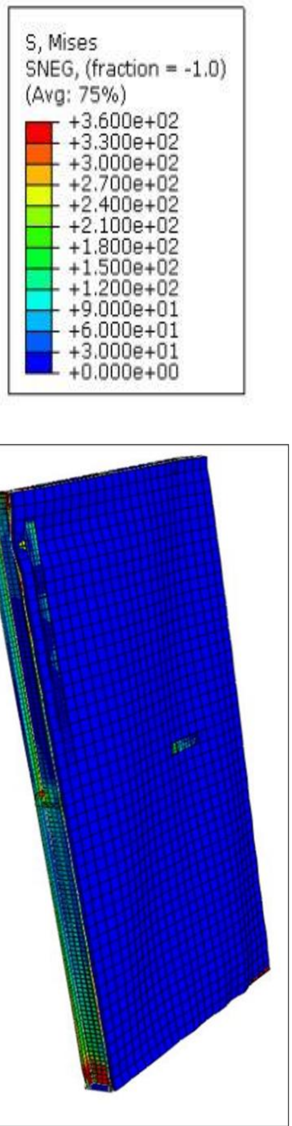


Fig.10 Sheathing to Frame Connection Failure

C. Deformation of CFS Frame Members

One advantage of the developed high fidelity shell FE models is the ability to capture all the buckling modes of the CFS frame members and visually represent the deformed shape and stress allocation in the shear wall. In particular, Fig. 11 provides the von Mises stress contour plotted on the distorted shape of the specimen for Model FCBM16 at peak load. Contour values are represented by a rainbow color spectrum ranging from red (highest value) to blue (lowest value). Von Mises stress is commonly used in determining whether isotropic metal yields when subjected to a complex loading condition. In this research, although cold-formed steel members are modeled as elastic, the plotted contours can suggest where to expect yielding to happen in the shear wall by setting the maximum limit for the contour as material's yield stress. The maximum limit for the contours shown in Fig.11, in particular, was set to 360 N/mm^2, which is the real yield stress of the CFS used for the test. The plots show a large stress concentration on the flanges of tracks near the stud-to-track connection and indicate that these areas should be expected to yield according to von Mises Yield Criterion.



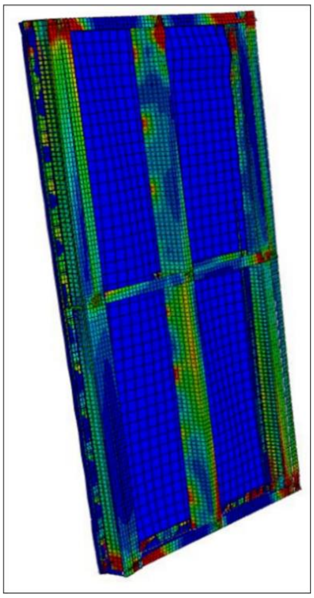


Fig.11. Von Mises stress contour plotted on the deformed shape of FCBM16

V. CONCLUSIONS

There is a development of high-fidelity computational modeling of FCB and gypsum sheathed CFS framed shear wall, which was initiated in Abaqus. The developed modeling protocol was demonstrated to be able to capture lateral load-carrying capacity with reasonable accuracy.

Load vs. deflection graphs are plotted for shear walls without sheathing and with sheathing by different materials and thickness. It was found that the ultimate load-carrying capacity of shear wall with FCB having a thickness of 8mm was 63 kN which is more than 166.4 % as compared to the Shear wall without sheathing, i.e., 23.65 kN. Also, displacement due to frame with FCB is 54.82 mm that is 5.6% less than that of only frame displacement of 58.11 mm. From this, it can be concluded that sheathing improves the lateral load-carrying capacity.

The comparison of shear wall sheathed with Gypsum having 12 mm thickness and sheathed with FCB panel having 12mm thickness, shows the load-carrying capacity of Gypsum board and FCB board with given thickness is 68.75 kN and 68.82 kN respectively. Also, the maximum deflection was found to be 70.02mm and 61.68mm for Gypsum and FCB board, respectively. The lateral load-carrying capacity of both the material is approximately equal, but maximum deflection in the FCB board is 0.12% less than the Gypsum board. So, the use of an FCB board for sheathing with 12mm thickness is recommended.

Comparison between Shear wall sheathed with FCB board having thicknesses as 8mm, 12mm and 16mm, it was observed that the lateral load-carrying capacity of the board with 16mm thickness is highest which is 70.64 kN and for 12 mm thickness and 8 mm thickness it is 68.82 kN and 63 kN respectively. The capacity for a load of 16mm board is more than 2 % that of 12mm board and 11% that of 8mm FCB board. Maximum deflection is shown by 12mm thick board as 61.68mm, and by 8mm and 16mm, the board is 54.82mm and 52.91 mm, respectively. The least deflection is shown by 16mm board which is 14%less and 3.5% less than 12mm and 8mm thick FCB board. So, it can be concluded that the more thickness, the more the capacity.

Comparison between the shear wall sheathed with Gypsum board having thicknesses 12 mm and 16mm; it is seen that the load-carrying capacity by 12 mm board is 68.75 kN and by 16mm board is 70.64 kN which is 2.7% more than that of 12 mm board. Also, maximum deflection by 16mm board is 61.59 mm and by 12 mm board is 70mm, which is more than 14% than 16mm board. So, from this observation, it can be concluded that higher thickness has higher capacity and comparatively less deflection.

The failure mechanism of sheathing-to-frame connections as well as deformation of CFS frame members was presented. A large stress concentration was found at the flanges of tracks near the stud-to-track connection. So Additional bracing members can be used for future work.

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