Numerical Investigation of Double-Skin Cold-Formed Steel Shear Wall Filled with Concrete

Vlaho Žuvelek, Ivan Ćurković(✉), Ivan Lukačević, and Andrea Rajić

Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia
ivan.curkovic@grad.unizg.hr

Abstract. Steel and composite shear wall systems are used for vertical stabilisation of buildings and have been widely investigated in recent decades. Such systems provide excellent shear strength and ductility while allowing material savings due to optimal material usage and an increase in construction speed. A double-skin cold-formed steel shear wall filled with concrete is an innovative composite shear wall that is composed of cold-formed corrugated steel sheets and intermediate fasteners filled with concrete which is in turn bounded by a steel frame. Steel sheets are connected onto a concrete core with the help of intermediate fasteners behaving as shear connectors forming a sandwich Steel–Concrete–Steel panel. Compared to reinforced concrete shear walls, this type of wall has enhanced strength and ductility due to steel confinement while allowing for a reduction in construction time. The numerical simulation of double-skin cold-formed steel shear walls filled with concrete has been studied in this paper. The numerical parametric simulations are conducted in ABAQUS/CAE, where the influence of steel sheet thicknesses, concrete strength and the arrangement and diameter of the shear connectors were analysed. The wall shear capacities for all parameters were compared and the results provide suggestions for future investigations.

Keywords: Cold-formed steel · shear wall · corrugated steel sheeting · double-skin · composite systems · monotonic load

1 Introduction

In recent years, light-framed cold-formed steel (CFS) structures have been widely used in North America, Australia and Japan, particularly for low and medium-rise buildings. The CFS system is rightly being more popular precisely because of the numerous advantages that characterise it. Such lightweight systems in particular are considered to be cost-effective systems that offer convenient modular design, high strength, efficient mechanical assembly, recyclable components and good seismic behaviour [1–4]. Due to the significant structural and ecological efficiency of CFS lightweight structures, research interest has increased significantly in improving the behaviour of such systems in high seismic areas for mid-rise and high-rise buildings. However, the lack of such a system in mid-rise and high-rise buildings is precisely the insufficient lateral resistance

V. Ungureanu et al. (Eds.): CESARE 2024, LNCE 489, pp. 105–115, 2024.
https://doi.org/10.1007/978-3-031-57800-7_9

to absorb horizontal forces due to earthquakes or strong winds [5]. Therefore, the shear walls are an indispensable part of such CFS building systems because they are primarily lateral force-resisting elements that also transfer the vertical load [6, 7]. Through various research and practises, there are numerous types of sheeting, including gypsum board, cement particle board, plywood, oriented strand board (OSB), steel sheets and corrugated web.

The beginnings of research into the behaviour of CFS shear walls were started by Fülöp and Dubina [8]. As part of this research, a series of full-scale monotonic and cyclic tests of shear walls with different types of sheeting materials such as corrugated steel sheets, OSB and gypsum board were carried out. The research has shown that the failure of corrugated shear walls is due to damage to the seam fasteners and subsequent failure of the corrugated panel. However, it was ultimately concluded that CFS shear walls with corrugated sheeting exhibit a rigid behaviour and can effectively resist lateral loads. The researchers also suggested increasing the load-bearing capacity and ductility of the seams fasteners to improve the performance of the shear wall. A more extensive study was carried out by Stojadinavić and Tipping [9], in which a series of 44 tests were performed on CFS shear walls with corrugated steel sheeting. In the tests, a total of six parameters varied between samples, such as the geometry of the profile and corrugated sheeting, the type, size and spacing of the fasteners, the inclusion of additional gypsum boards on one side and the application of single-skin or double-skin corrugated sheeting on the side of the CFS shear walls. In the end, the researchers concluded that in all samples, the fasteners were pulled out through the wrap of the corrugated sheeting, creating diagonal tension and compressive areas. The continuation of this research was conducted by Yu et al. [10], where the influence of the thickness of the frame members, the size and spacing of the fasteners and the configuration of the boundary members on the behaviour of CFS shear walls was investigated. In the studies by Yu et al. [10] and Zhang et al. [11–13], a corrugated steel sheeting is attached to the surface of the CFS frame elements. Such a shear wall configuration has shown good behaviour with high strength and stiffness. Furthermore, based on the research on the behaviour of CFS shear walls with corrugated steel sheet, it was concluded that corrugated sheet has higher strength and stiffness compared to some conventional sheets such as flat steel sheets, wood panels and OSB. However, the results of the study by Fülöp and Dubina [8] show that the loading method has no significant effect on the stiffness of the CFS shear wall, but the ductility of the wall is slightly lower under cyclic loading than under monotonic loading. This behaviour is caused by the failure of the fasteners to the corrugated sheet. To improve the behaviour of the wall in this respect, a series of tests using corrugated sheets with different types of openings were conducted [14, 15]. The idea of corrugated sheeting with openings allows for localised weakening of the sheeting stiffness and at the same time out-of-plane buckling and tearing of the panel around the opening. At the same time, it is assumed that there will be no sudden drop in the shear strength of the wall and an increase in the capacity for energy dissipation under cyclic loading is expected. Such a change in force transmission can prevent or partially reduce the failure of fasteners. In the study [14, 15], circular holes and slit openings were investigated and in the end, it turned out that the proper slit openings in the sheeting provided satisfactory ductility of the shear wall while maintaining significant strength and initial stiffness. Furthermore, research on the behaviour of lateral resisting systems has shown that the application of a concrete layer allows a more even distribution of stress in steel shear walls. Such behaviour improves the system performance and leads to maximum utilisation of the shear capacity of the shear wall [16, 17].

This research aims to develop the idea of the moment-resistant frame with an innovative bracing system such as a CFS shear wall with double-skin corrugated sheeting with an intermediate concrete layer. Such a system could potentially be used in high seismic areas for medium-rise and high-rise buildings, as the energy can be dissipated at the designated locations and the shear walls can be replaced, which would reduce repair costs. This paper provides a preliminary insight into the behaviour of a CFS shear wall with a double-skin corrugated sheeting with an intermediate concrete layer (DCSWC). Finite element analysis was used to validate the model of the CFS shear wall with single-skin corrugated sheeting according to the tests [18], which will then serve as a benchmark model for the development of the model with a double-skin concrete layer.

2 Finite Element Modelling

2.1 Development of FE Models

The finite element analysis was performed with the Abaqus Explicit Solver to cover geometric and material nonlinearities. The finite element modelling method used in this study is similar to that of Mahdavian [18]. The shear wall with the dimensions of 2.4 $\times$ 1.2 m consists of vertical framing members with a cross-section of 350 S 200-68, horizontal framing members with a cross-section of 350 T 150-68 and the corrugated steel sheeting Verco Decking SV36, as shown in Fig. 1. Given that the study [18] does not explicitly address any imperfections, they have not been incorporated into the numerical model. The material properties of the CFS elements are defined by the bilinear elastic-plastic material model. The general parameters of the material model are the modulus of elasticity and Poisson's ratio, which were assumed to be 203.4 GPa and 0.3, respectively. True stress-strain curves were adopted based on experimental test results of the CFS base material [18]. The connection between the corrugated steel sheeting and framing members is achieved using screws. The connection between two sheetings is also made in the same way, considering that the shear wall consists of three sheetings over its height. In the numerical model, the simulation of the behaviour of the screws was realised with the Connector Builder through the implementation of the corresponding connector section. For the corresponding connection, screw stiffness is defined in the vertical and horizontal directions based on the connection test results provided in [18]. However, since no failure occurred in the connections between the frame members, tie constraints were assumed for stud-to-stud and stud-to-track connections. The boundary conditions are simplified compared to the experimental samples. Therefore, displacements and rotations in all three directions are prevented at all points of the web of the bottom track as well as the bottom contour of the cross-section of the studs. The hold-down area of each chord stud is simulated in such a way that vertical displacements are prevented at all points in this area. To ensure that out-of-plane displacement of the shear wall does not occur, out-of-plane displacements were prevented at the points of the upper track flanges to simulate lateral support in the actual experiment. In addition, all points of the web of the upper track are connected to the coupling constraints with a reference point. The reference point is located at the edge of the top track through which the horizontal load application was realized using the displacement control method. The interaction between sheeting and framing members is defined by surface-to-surface contact, using normal and tangential behaviour. The definition of normal behaviour (hard contact) prevents penetration of the sheeting through the frame members or vice versa, while tangential behaviour is simulated using the penalty frictionless method. All parts of the model were modelled using shell elements (S4R). The global mesh size is 38 mm for the corrugated sheeting and 12 mm for the framing members (studs and tracks).

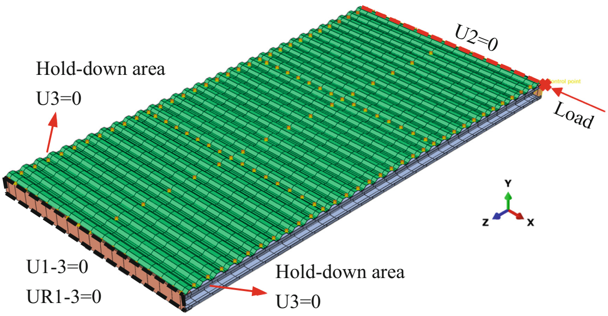


Fig. 1. Numerical model based on Test 54 by Mahdavian [18].

As already mentioned, the model from Fig. 1 will serve as a benchmark model for modelling a double-skin CFS shear wall filled with concrete (DCSWC). The DCSWC model contains a profiled sheeting on both sides of the CFS frame, between which a concrete layer is embedded, as shown in Fig. 2. The modelling of the connection of the sheeting and framing members is adopted as in the benchmark model, while the connection of the double-skin sheeting through the concrete is realised using bolts. The positions of the bolts are shown in Fig. 2. The bolts are modelled as beam elements (B-31) with associated material properties such as yield strength and strength, whose values are 240 and 400 MPa. To simulate the behaviour of the concrete wall, the CDP model was used, for which the plasticity parameters were assumed as in [19]. Furthermore, the bolts and the individual framing members were embedded in the concrete wall to simulate the contact between bolts and CFS elements with concrete. The bolts were attached to the corrugated sheeting with the "MPC tie" constraint. To simulate the contact between concrete and corrugated sheets, surface contacts were used that define the normal behaviour and the tangential behaviour with a friction coefficient of 0.15. In addition, the general contact was used for whole model to consider any new contact arise during the analysis. For the general contact, the contact property with normal and tangential behaviour was used, assuming a friction coefficient as frictionless. The concrete slab was modelled with a solid element (C3D8R), using a global mesh of 30 mm.

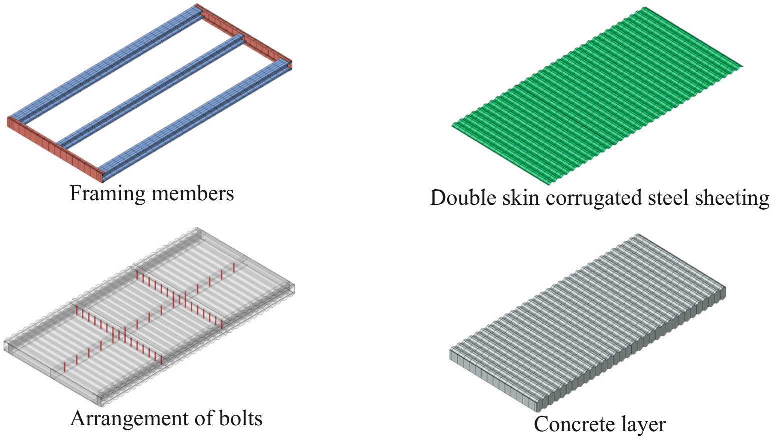


Fig. 2. Components of the model of double skin CFS shear wall filled with concrete.

2.2 Model Validation

The results of the numerical analysis were compared with the experimental results of Test 54 by Mahdavian [18] to establish a validated model. The numerical load-displacement curve shows a good agreement with the experimental curve, as shown in Fig. 3. Also, the compared characteristic values are shown in Table 1.

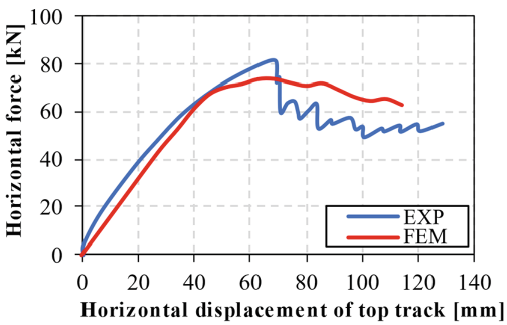


Fig. 3. Comparison of experimental and numerical curve.

Table 1. Comparison of experimental and numerical results.

	P_{ult} [kN]	Ratio	Δ_{ult} [mm]	Ratio
Experimental	80.8	**0.92**	68.4	**1.00**
Numerical	73.9		68.5	

Furthermore, a detailed investigation of the numerical model revealed buckling of the corrugated sheeting in the bottom zone of the shear wall accompanied by slight torsional and localised buckling of the vertical framing members. These failure modes were also observed in experimental tests, as shown in Fig. 4. Therefore, this model was used as a benchmark model to model a double-skin cold-formed steel shear wall filled with concrete (DCSWC).

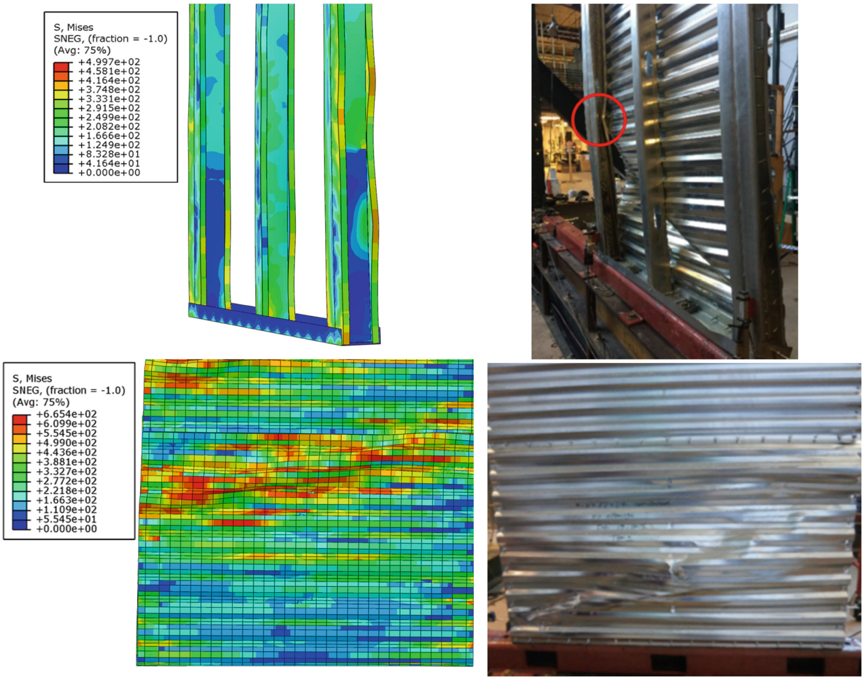


Fig. 4. Comparison of failure modes between numerical model and experimental tests.

3 Parametric Study

The parametric analysis provides an even better insight into the behaviour of DCSWC. Therefore, the parameters that were assumed to influence the behaviour were varied, such as the concrete strength, the thickness of the corrugated sheeting, the diameter of the bolts and the arrangement of the bolts. Table 2 lists all the varied parameters, while Fig. 5 shows the considered cases of bolts arrangement.

Figure 6 shows the numerical load-displacement curves for all models considered in the parametric analysis. Although all models experienced buckling of vertical framing members with the formation of diagonal damage and damage in the slab along the central frame member, differences in the behaviour of the individual models were observed. Therefore, by increasing the strength of the concrete, it was observed that greater shear wall resistance is achieved. However, it can also be seen that the model with lightweight concrete achieves a similar resistance to the model with normal-weight

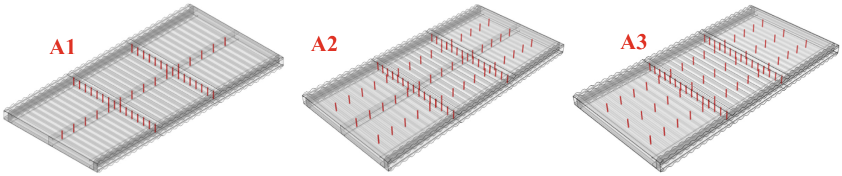


Fig. 5. Arrangement of bolts.

Table 2. Specifications of parameters varied within the parametric study.

Model name [DSWC_xx]	Concrete class	Thickness of corrugated sheathing [mm]	Diameter of bolts	Arrangement of bolts
C20/25	**C20/25**	0.68	M12	A1
C30/37	**C30/37**			
LC20/22	**LC20/22**			
CS068	C20/25	**0.68**	M12	A1
CS10		**1.0**		
CS15		**1.5**		
M10	C20/25	0.68	**M10**	A1
M12			**M12**	
M16			**M16**	
A1	C20/25	0.68	M12	**A1**
A2				**A2**
A3				**A3**

concrete, whereby the weight of the shear wall is significantly reduced. Further detailed examination of the model revealed that the concrete in the model (DCSWC_LC20/22) fractures significantly without forming expected diagonal tension and compression damage as has occurred in the model with normal concrete, as shown in Fig. 7. Changing the thickness of the double-skin corrugated sheeting leads to a slight increase in resistance. Also, according to the shape of the curve, it can be observed that increasing the thickness of the double-skin corrugated sheeting tends to result with a higher yield strength of the shear wall. Furthermore, changing the diameter of the bolts has no significant effect on the behaviour of the shear wall. Also, the arrangement of the bolts (DCSWC_A2) does not contribute to a significant difference in the resistance of the shear wall compared to the base model (DCSWC_A1), while it does contribute to the wall ductility. However, the model with an A3 arrangement of the bolts (DCSWC_A3), which does not include a central frame member, shows a difference in resistance and ductility compared to the base model with a smaller number of bolts. In addition, such a model without a central frame member diagonally damages along the width of the wall. From this, we can conclude that the central frame member contributes significantly to the resistance and ductility of the shear wall and ultimately to the development of diagonal damages in concrete.

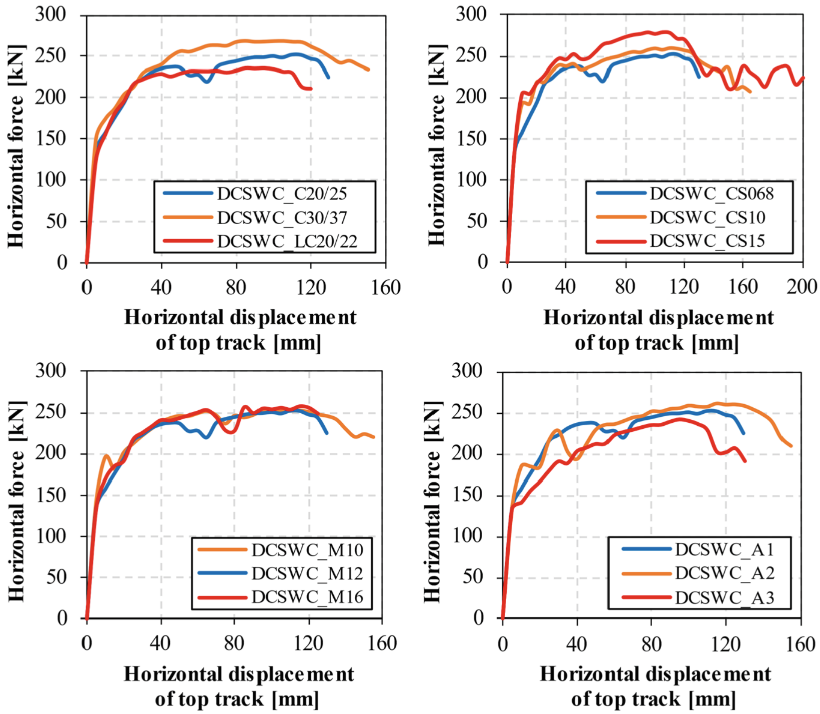
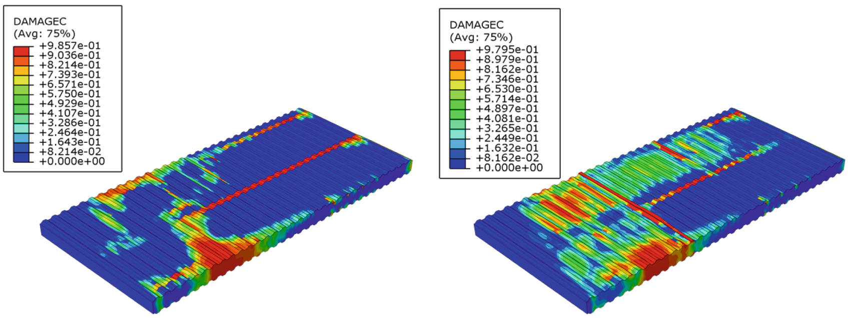


Fig. 6. Load-displacement curves for parametric models.



a. DCSWC_C20/25 b. DCSWC_LC20/22

Fig. 7. Compression damage of concrete slab.

4 Conclusions

In this study, a preliminary numerical analysis of the behaviour of a double-skin CFS shear wall filled with concrete under the influence of a monotonic load was performed. First, the finite element modelling technique for a single-skin CFS corrugated shear wall without a concrete layer was presented. Then, the modelling technique was validated with a reasonable agreement between experimental and numerical results. A parametric analysis was performed to gain knowledge and insight into the influence of individual parameters on the behaviour of the double-skin CFS shear wall filled with concrete. Based on the results of the parametric analysis following conclusions can be provided:

- The change in concrete strength contributes to the increase in shear wall resistance. In addition, when using lightweight concrete, it is possible to achieve similar resistances to normal concrete, while significantly reducing the weight of the system itself.
- Models with lightweight concrete cause more sudden fractures in the concrete and insufficient formation of diagonal damages in the concrete slab.
- Changing the thickness of the corrugated sheeting slightly affects the resistance of the shear wall. In addition, increasing the thickness of the corrugated sheeting tends to result with a higher yield strength of the shear wall.
- The diameter of the bolts that are embedded into the concrete has no significant influence on the behaviour of the shear wall. However, it was found that the arrangement of the bolts as well as the presence of the central frame member can significantly influence the behaviour of the shear wall in terms of resistance and ductility.

This study is an introduction to the research of a new shear wall system that can be used as an innovative bracing system in highly seismic areas. However, further experimental and numerical studies under cyclic loading are required, which will give a better insight into the behaviour of the shear wall. Also, the connection of the CFS shear wall to the steel frame structure needs further research so that the wall can be dismantled after its inelastic deformation and replaced by a new CFS shear wall.

Acknowledgement. This research was partially funded by the Croatian Science Foundation, grant number UIP-2020-02-2964 (LWT-FLOOR project-Innovative lightweight cold-formed steel–concrete composite floor system), project leader: Ivan Lukačević and the COST Action CircularB - Implementation of Circular Economy in the Built Environment.

References

1. Derveni F, Gerasimidis S, Peterman KD (2020) Behavior of cold-formed steel shear walls sheathed with high-capacity sheathing. Eng Struct 225:111280
2. Tian YS, Wang J, Lu TJ (2004) Racking strength and stiffness of cold-formed steel wall frames. J Constr Steel Res 60:1069–1093
3. Serrette R, Hall G, Nguyen H (1996) Dynamic performance of light gauge steel framed shear walls. In: CCFSS Proceedings of International Specialty Conference on Cold-Formed Steel Structures (1971 - 2018)

4. Serrette R, Ogunfunmi K (1996) Shear resistance of gypsum-sheathed light-gauge steel stud walls. J Struct Eng 122:383–389
5. Zhang W, Mahdavian M, Lan X, Yu C (2021) Cold-formed steel framed shear walls with in-frame corrugated steel sheathing. J Struct Eng 147:1–10
6. Javaheri-Tafti MR, Ronagh HR, Behnamfar F, Memarzadeh P (2014) An experimental investigation on the seismic behavior of cold-formed steel walls sheathed by thin steel plates. Thin-Walled Struct. 80:66–79
7. Shamim I, DaBreo J, Rogers CA (2013) Dynamic testing of single- and double-story steel-sheathed cold-formed steel-framed shear walls. J Struct Eng 139:807–817
8. Fülöp LA, Dubina D (2004) Performance of wall-stud cold-formed shear panels under monotonic and cyclic loading - Part I: experimental research. Thin-Walled Struct. 42:321–338
9. Tipping S, Stojadinovic B, Foundation CP (2008) Innovative Corrugated Steel Shear Walls for Multi-Story Residential Buildings, The 14th World Conference on Earthquake Engineering, Beijing, China
10. Yu C, Huang Z, Vora HD (2009) Cold-formed steel framed shear wall assemblies with corrugated sheet steel sheathing. In: Proceedings of the Annual Stability Conference, Structural Stability Research, pp 257–276, Phoenix, United States
11. Zhang W, Mahdavian M, Li Y, Yu C (2017) Experiments and simulations of cold-formed steel wall assemblies using corrugated steel sheathing subjected to shear and gravity loads. J Struct Eng 143:1–13
12. Zhang W, Mahdavian M, Li Y, Yu C (2016) Simulating the seismic performance of cold-formed steel framed buildings using corrugated sheet shear walls. In: International Specialty Conference on Cold-Formed Steel Structures, pp 785–794, Baltimore, Maryland
13. Zhang W, Mahdavian M, Yu C (2018) Lateral strength and deflection of cold-formed steel shear walls using corrugated sheathing. J Constr Steel Res 148:399–408
14. Yu C, Yu G (2016) Experimental investigation of cold-formed steel framed shear wall using corrugated steel sheathing with circular holes. J Struct Eng 142:1–9
15. Yu C, Zhang W, Yu G, Wang J (2018) Cold-formed steel shear wall using corrugated steel sheathing with slits. J Struct Eng 144:1–11
16. Rahai A, Hatami F (2009) Evaluation of composite shear wall behavior under cyclic loadings. J Constr Steel Res 65:1528–1537
17. Ćurković I, Skejić D, Džeba I, De Matteis G (2019) Seismic performance of composite plate shear walls with variable column flexural stiffness. Steel Compos Struct 33(1):19–36
18. Mahdavian M (2016) Innovative Cold-Formed Steel Shear Walls With Corrugated Steel Sheathing. Master Thesis
19. Žuvelek V, Ćurković I, Lukačević I, Rajić A (2022) Numerical study of the behavior of the bolted shear connection in cold-formed steel-concrete composite beam. In: Proceedings of the Cold-Formed Steel Research Consortium Colloquium, Baltimore, United States