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A new precast wall connection subjected to monotonic loading

Ramin Vaghei[1a], Farzad Hejazi[*1,2], Hafez Taheri[1b], Mohd Saleh Jaafar[1c] and Abang Abdullah Abang Ali[2d]

[1]Department of Civil Engineering, Faculty of Engineering, University Putra Malaysia, Malaysia
[2]Housing Research Centre, Faculty of Engineering, University Putra Malaysia, Malaysia

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Abstract. Final construction project cost is significantly determined by construction rate. The Industrialized Building System (IBS) was promoted to enhance the importance of prefabrication technology rather than conventional methods in construction. Ensuring the stability of a building constructed by using IBS is a challenging issue. Accordingly, the connections in a prefabricated building have a basic, natural, and essential role in providing the best continuity among the members of the building. Deficiencies of conventional precast connections were observed when precast buildings experience a large induced load, such as earthquakes and other disasters. Thus, researchers aim to determine the behavior of precast concrete structure with a specific type of connection. To clarify this problem, this study investigates the capacity behavior of precast concrete panel connections for industrial buildings with a new type of precast wall-to-wall connection (i.e., U-shaped steel channel connection). This capacity behavior is compared with the capacity behavior of precast concrete panel connections for industrial buildings that used a common approach (i.e., loop connection), which is subjected to monotonic loading as in-plane and out-of-plane loading by developing a finite element model. The principal stress distribution, deformation of concrete panels and welded wire mesh (BRC) reinforcements, plastic strain trend in the concrete panels and connections, and crack propagations are investigated for the aforementioned connection. Pushover analysis revealed that loop connections have significant defects in terms of strength for in-plane and out-of-plane loads at three translational degrees of freedom compared with the U-shaped steel channel connection.

Keywords: industrial building systems; precast concrete structures; wall connection; monotonic loading; pushover analysis; finite element analysis

1. Introduction

Given its advantages, such as considerable savings in labor and material, enhanced product

∗Corresponding author, Senior Lecturer, E-mail: farzad@fhejazi.com
[a]Ph.D. Candidate, E-mail: ramin.vaghei@gmail.com
[b]Msc., E-mail: hafeztaheri@gmail.com
[c]Professor, E-mail: msj@ eng.upm.edu.my
[d]Professor, E-mail: aaaa@upm.edu.my

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quality and workmanship, and the rate of construction, precast concrete construction has been marketed in the past half century (Yee and Eng 2001). Statistics show that countries such as Malaysia, Japan, Singapore, United States, and United Kingdom have a greater tendency to use systems such as Modern Methods of Construction (MMC) worldwide or particularly addressed as Industrialized Building Systems (IBS) in Malaysia. MMC or IBS is a term that is commonly used to identify the construction method in which precast elements are produced in a controlled environment and carried, located, and erected into a structure with minimal necessary site work. The other concepts are Open Building Systems and Modular Coordination (Nawi *et al*. 2009).

Yee and Eng (2001) studied the precast concrete structures and determined that considering the suitable connection is more important than considering ordinary structures. Mechanical connection devices have advanced significantly and have become reliable, and the so-called failsafe connections in particular have been developed for precast concrete members in recent years. Indeed, these connections for precast concrete should be emulated in terms of strength and overall continuity by using the same in situ connection. According to the guide report by the American Concrete Institute Committee 550, emulative detailing is “the design of connection systems in a precast concrete structure so that its structural performance is equivalent to that of a conventionally designed cast-in-place, monolithic concrete structure” (Institute 2009). Ericson (2010) proposed a connection for precast members in which the behavior of the reinforcement steel and concrete is similar to that in cast-in-place connection to improve a monolithic system. Therefore, the use of precast members in the structure raises a common concern about maintaining structural continuity with the connections that are considered through precast sections. The parameters that are considered in designing connections for precast members should be the same as those in the emulating cast-in-place connection (Jansson 2008). This concern is important in prefabricated walls particularly when the walls need to bear vertical and horizontal loads. The quality of connections and integration of buildings play a significant role in structural stability. Load-bearing precast concrete wall panels act as structurally efficient members. Freedman (1999) showed that economical means of transferring floor and roof loads into the foundation exist. This integration of structurally efficient and economical means of transferring loads reduces production costs and leads to the extensive use of these methods. Thus, finding a reliable connection for the load-bearing walls encourages contractors to use precast concrete structures and to gain the advantages of such structures.

Many methods and types of connections are used to connect members of precast concrete structures. Two points are considered in designing connections. The first point is the kind of members that are connected to one another, for which the suitable connection is chosen according to type. The second point is the forces that the connection should transfer and the forces that prevent the transfer. Certain joints are used to connect precast beams to column. An embedded steel section is present in some joints. These joints should be located in the correct place before concreting. Then, they are welded and/or bolted. Slightly wet concrete is sometimes used to fireproof the connection. Some studies discussed this kind of beam-to-column connection (Bhatt and Kirk 1985), (Choi *et al*. 2013). In the other kind of joints, the connection between the precast member and cast in situ concrete is made by wet concrete. This type of joint involves minimal additional site work, such as welding or bolting, and it is popular and widely investigated (Khaloo and Parastesh 2003, Khoo *et al*. 2006, Parastesh *et al*. 2014, Xue and Yang 2010). Unal and Burak (2012) numerically studied the prior arts on reinforced concrete beam-column connection subjected to cyclic loading and developed an equation by considering of parameters such as eccentricity, column axial load, wide and transverse beam and so forth. Precast panels and diaphragms also have distinct connections to carry and transfer loads. The function of the connection becomes complicated when the connection is subjected to live and seismic loads. The boundary edges of the joint in the design of diaphragm connections should resist compression and tension forces that result from bending of the diaphragm. The intermediate connections should resist shear forces among the diaphragms. In addition, many researchers investigated mechanical connectors and wet connections for precast concrete diaphragms (Blandon and Rodriguez 2005, Bournas *et al*. 2013, Cao and Naito 2009, Naito *et al*. 2009, Pincheira *et al*. 2005).

The kind of connections and the type of joints in bearing precast walls are important. Precast wall designs should be able to handle vertical or lateral loads. Foerster *et al*. (1989) reported that precast load bearing shear wall panels have been commonly used in high-rise constructions over the past decades. These panels are popular in the construction industry because of good quality control of precast walls in the manufacturing plant and ease of erection and installation on site. Several investigations and experimental studies on different shapes of connections for precast concrete walls discussed façades, cladding, and shear walls (Biondini *et al*. 2012, Bora *et al*. 2007, Shultz *et al*. 1994). Pantelides *et al*. (2003) investigated the use of high-strength materials, such as CFRP, as connectors for precast walls. Defects of precast wall panel connections were revealed when many precast buildings were destroyed in disasters such as the earthquakes in Adana Ceyhan (1997) and Koaceli and Duzce (1990) and the Ronan Point disaster in London. Precast concrete walls are detached from one another because of building demolition. Holden *et al*. (2003) investigated seismic behavior of two types of precast concrete cantilever wall, one was cast-in-place concrete wall based on code compliance and the other one was precast partially prestressed concrete wall. It was concluded that the former system dissipates more energy than the latter one which results in higher residual deformation. Therefore, further research was conducted to investigate the behavior of precast wall connections in seismic zones (Biondini *et al*. 2013, Holden *et al*. 2003, Negro *et al*. 2013, Pennucci *et al*. 2009, Smith and Kurama 2009).

Joints between wall panels can be classified into vertical joints, which have an important role in the response of structure, and horizontal joints.

Some researchers assumed that the concrete in the vertical joint zone has low stiffness compared with the concrete in the wall panels (Chakrabarti *et al*. 1988, Foerster *et al*. 1989). The other kind of joint is horizontal joints at the floor levels. Jansson (2008) showed that horizontal joints are much stiffer than vertical joints because of the normal pressure applied on the joints. One of the common connections in horizontal joints is the splice sleeve. Splice sleeves consist of Lenton Interlok rebar splicing system and NMB Splice Sleeve System splicing connectors. Hamid and Mander (2010) investigated the seismic resistance of precast hollow core wall units and reported that no cracks observed either on seismic walls or nonseismic walls up to 4.0% drift. Pavese and Bournas (2011) conducted seismic tests on single and 2-storey fullsclae walls and found that there is a strong coupling between shear and flexure through the performance and failure mode of all panels. Many techniques were developed to protect the structures subjected to dynamic and earthquake loads (Hejazi Farzad *et al*. 2011, Hejazi F *et al*. 2013).

Another type of connection that is widely used in precast walls and beams is loop connection. This kind of joint is a wet connection, and cast-in-place concrete is used instead of joint. The reinforcement and loops need to overlap to ensure integrated connection. Projecting bars or full 180 hooks are installed in each prefabricated wall. Moreover, these projecting bars or full 180 hooks overlap one another instead of the joints during concreting or grouting. The transverse reinforcement should pass through the loops to prevent brittleness. Splitting usually occurs at the plane of the loop. Recent studies investigated and tested the behavior of loop connection under different loading situations (Araújo *et al*. 2014, Ong *et al*. 2006a, 2006b, Rossley *et al*. 2014). Vaghei *et al*. (2014) performed nonlinear static (pushover) and dynamic analyses under recorded and artificial earthquakes, and the role of wall panel connections on the seismic behavior of the structural assembly was recorded. Solak *et al*. (2015) reported that anchored connection in wall panels subjected to reversed cyclic load cannot be designed for high ductility levels due to local formation of cracks vicinity of connection. Peng *et al*. (2015) studied a mortar-sleeve connection in concrete shearwalls subjected to cyclic loads and concluded that tensile stress of longitudinal reinforcement can effectively transferred by steel sleeves. Furthermore, it was shown that horizontal cracks occurred above the steel sleeves; however, the failure mode in mortar-sleeve connection in precast shear wall is similar to the failure mode of cast-in-place shearwall.

Unlike in situ concrete systems, different parts of IBS, particularly the connections, have not been studied extensively. Moreover, no clear regulations and provisions exist for the construction of precast concrete structures. According to investigations on different disasters, precast wall connections have a serious problem with strength. In this study, a new ductile connection is developed for precast concrete wall panels and is subjected to monotonic loading. The main advantages of the proposed connections compared with the conventional precast connections are speed of construction, low cost, and reduced need for skilled labor. These advantages are achieved by minimizing cast-in-place concrete volume and eliminating the need for formworks and welding. The proposed detailing can also enhance the capacity of the connections and improve structural integrity among wall panels. The efficiency of the proposed system is investigated by comparing the performance of the proposed connection with the loop connection under monotonic loading by performing nonlinear static finite element analysis.

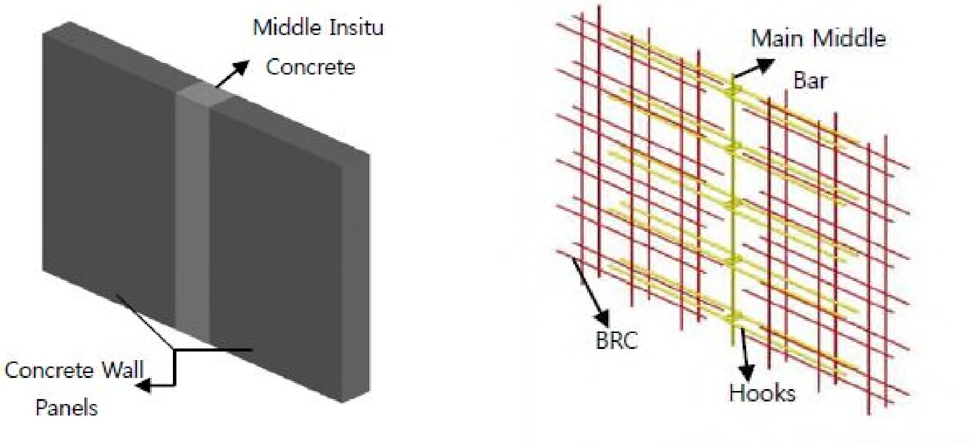
2. Precast wall connections

A connection should ensure the overall continuity of the structure and have suitable ductility and rigidity. For precast concrete structures, considering the suitable connection is more important than considering ordinary structures. The connections for precast concrete walls are vital when they carry vertical and lateral loads. These connections should be capable of transferring the load to another member of the structure and finally to the foundation of the building. Appreciated connection among walls guarantees the conducting load from one wall to the adjacent wall. Thus, these two walls work together. This connection should possess sufficient strength to carry loads and enough ductility.

These walls are used as exterior or interior walls of buildings, walls of lift cores, and parapets; not only on apartments and hotels with medium height but also on ordinary flats and homes with low height. Given that precast walls are produced in plants, the strength of concrete is determined and controlled accurately. The finished surface is so smooth that the walls are immediately ready for painting or wallpaper.

2.1 Loop connection

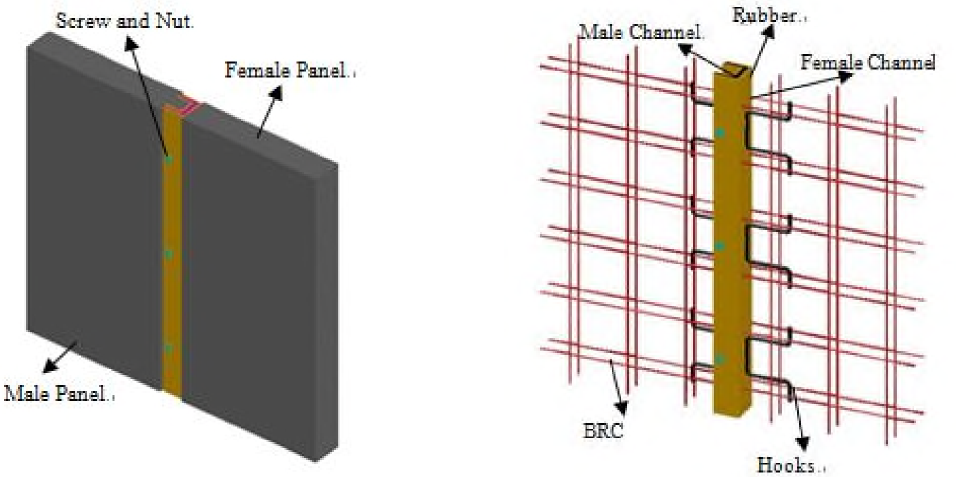
The details of loop connection are shown in Fig. 1. The model comprises two concrete wall panels, concrete reinforcing welded mesh (BRC), hooks, main middle bar, and in situ concrete. The loop connection is provided by anchor bars or loops from reinforcing bars anchored by grouting in recesses and cores. The joint is filled with joint concrete or grout.



(a) General view of loop connection (b) Reinforcement in loop connection

Fig. 1 Details of loop connections

Loop connection is used among concrete wall panels with required continuity. However, the production is difficult because of the projecting bars. Loop connections for precast walls in IBS buildings are generally designed based on numerical and experimental studies. In addition, these loop connections are designed to resist static axial force in plane compression. Moreover, the loop connection cannot provide enough strength for other DOFs, (e.g., out-of-plane loadings). Hence, the structural components do not provide the integrity required to resist lateral dynamic loading in all directions when this type of connection is used. Most existing connections are also highly dependent on the ability of workers to sporadically set the costly and time-consuming connections. This study developed a new connection for precast walls to compensate for the connection problems and to provide sufficient strength for wall joints in all directions(i.e., six DOF (6DOF)).



(a) General view of proposed connection (b) Reinforcement in proposed connection

Fig. 2 Details of U-shaped steel channel connection

Time and cost are the two main parameters in setting and fabricating the connections. The proposed connection aims to improve the desired integrity for structural components in any direction and to protect the structures against multi-support excitations. This study developed a new connection for precast walls to compensate for the connection problems and to provide sufficient strength for wall joints in all directions (i.e., 6DOF)

2.2 Proposed connection

The proposed connection is composed of male and female panels and channels, rubber, welded wire mesh (BRC) reinforcements, hooks, screw, and nut. The parts of the proposed connection and the reinforcement and loop location are shown in Fig. 2.

The multidirectional resistances of the proposed connection are according to 6DOF. Axial and shear forces, torsion, and bending moments are the DOF considered in the proposed connection design. The following solutions are directed to a 3D proposed connection and are not limited to any particular size or configuration.

3. Development of finite element model

This study attempted to develop a 3D actual finite element model for precast concrete wall connection under lateral loads and to show the adaptability of this model to different situations. Different steps of finite element development for loop connection and proposed connection were studied, and simulations were conducted in detail by using the finite element software Abaqus.

3.1 Proposed connection

Different pieces such as male and female panels, male and female channels, rubber, BRC, hooks, screw, and nut were used to make the proposed connection. These parts, along with the location of reinforcements and hooks for the proposed connection, are illustrated in Fig. 1.

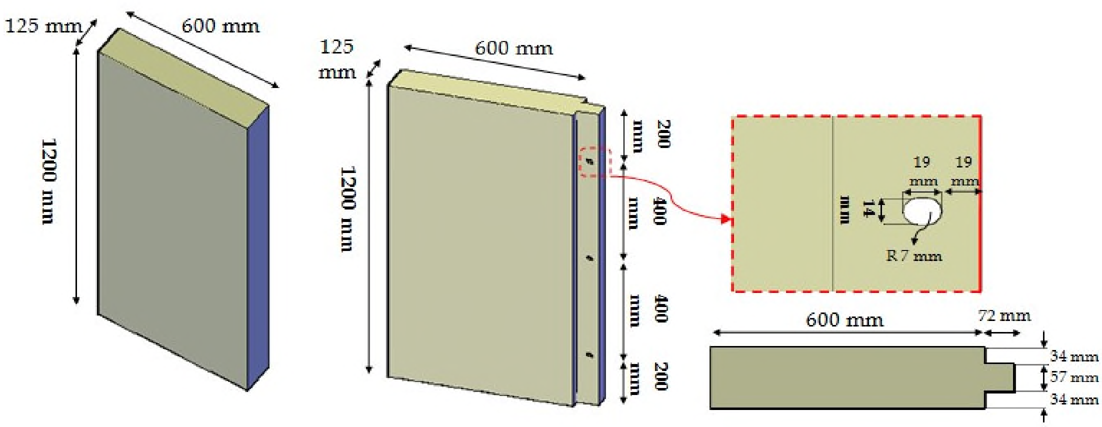


Fig. 3 Details and dimensions of concrete wall panels in proposed connection

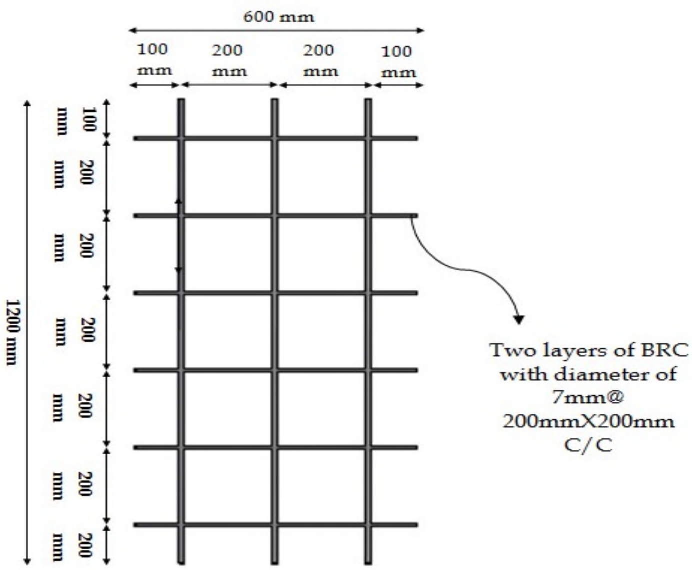


Fig. 4 BRC dimensions and details (mm)

Table 1 Parametric values

Dimension	Height (mm)	Web Thickness (mm)	Flange Thickness (mm)	Web Length (mm)	Flange Length (mm)	X(mm)
Female Channel	1200	8	8	105	90	28
Male Channel	1200	8	8	73	80	34
Rubber	1200	8	8	89	75	21

3.1.1 Concrete wall panel

The concrete wall panels included a male and a female panel. These panels were also modeled as solid parts for the proposed connection. Fig. 3 shows all the detailed dimensions of the concrete wall panels. A ridge was present at the end of the male panel with three holes to bolt the male panel to the female panel.

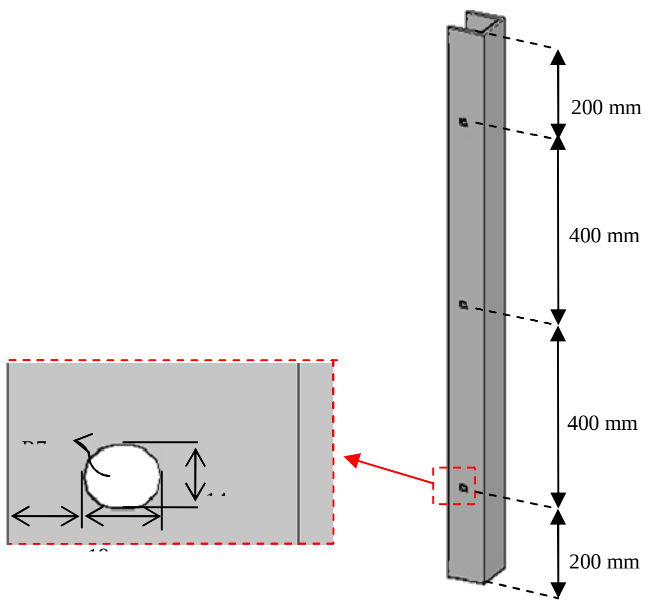
3.1.2 BRC

The reinforcements of concrete wall panels consisted of two layers of BRC-A7 mesh with a distance of 65 mm from center to center and a diameter of 7 mm. Horizontal distance and vertical distance of bars in each mesh were both 200 mm from center to center, as shown in Fig. 4.

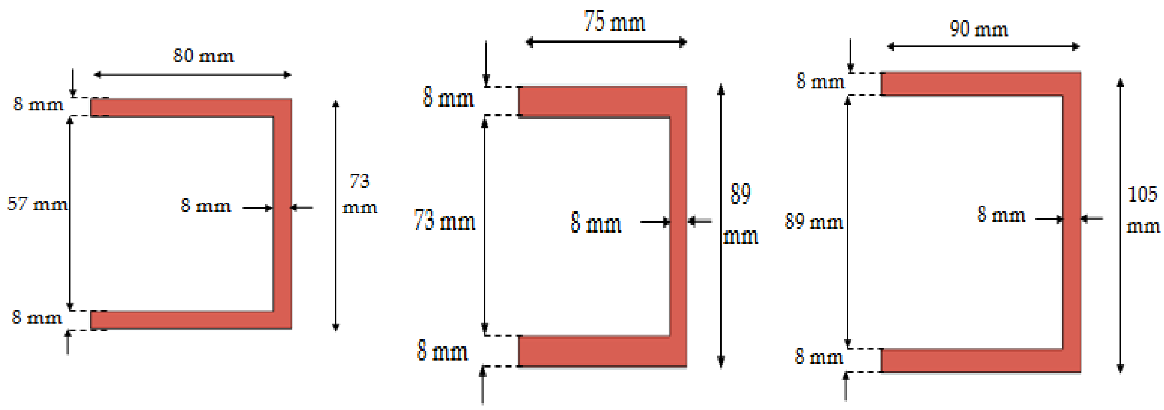
3.1.3 U-Shaped steel channel (female channel and male channel) and U-shaped rubber

All dimensions related to U-shaped steel channel (female/male) and U-shaped rubber are parametrically shown in Fig. 5(a), and Table 1 presents the parameter values.

Figs. 5(b)-(c)-(d) illustrate the cross sections of U-shaped female channel, U-shaped male channel, and rubber, respectively. These pieces were 8 mm thick and were defined as solid parts. The U-shaped steel channels with welded hooks should be embedded in concrete panels before



(a) Parametric U-shaped steel channel and U-shaped rubber



(b) U-shaped steel channel (female) (c) U-shaped rubber (d) U-shaped steel channel (male)

Fig. 5 Details and dimensions of female channel, male channel, and rubber in the proposed connection

concreting them in the proposed connection.

3.1.4 Hooks

Each U-shaped steel channel had three hooks to tie these channels with the concrete panel in the proposed connection. Fig. 6 shows the detailed dimensions of each hook with a 12 mm diameter.

3.1.5 Screw and nut

The function of screw and nut in the proposed connection was to fasten one part to the other part, such as the male channel, female channel, and rubber. The tolerance in the diameter of screw

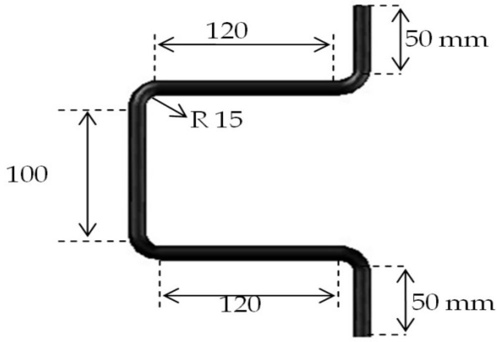


Fig. 6 Hook dimensions and details (mm)

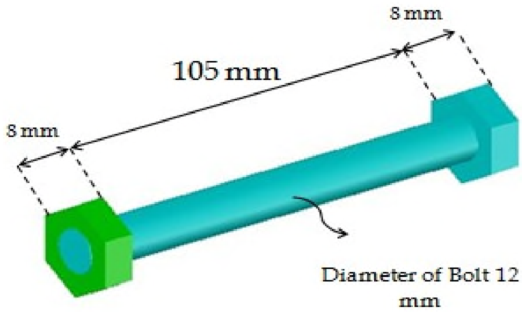


Fig. 7 Details and dimensions of rubber channel, screw, and nut

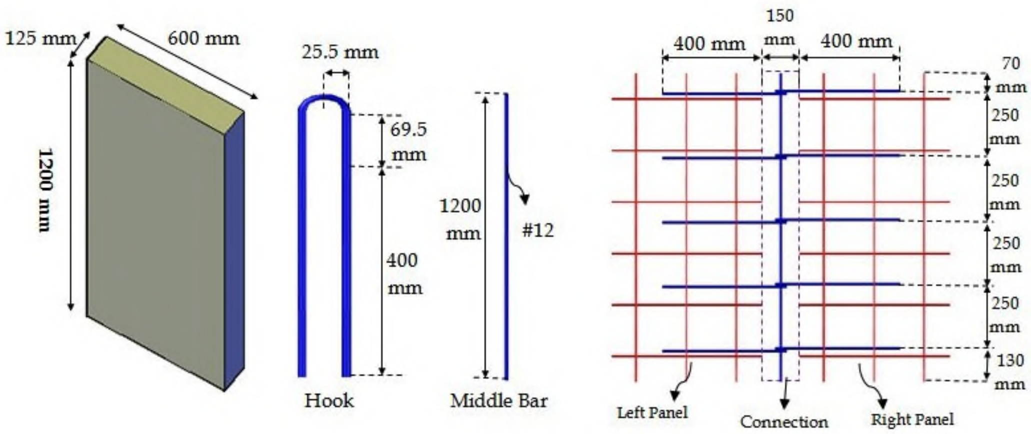


Fig. 8 Details and dimensions of concrete wall panels and reinforcements in loop connection

and nut was 2 mm. Screw and nut were modeled as solid parts by using the structured technique in Abaqus with detailed dimensions, as shown in Fig.7.

3.2 Components in loop connection

The details of loop connection, including two concrete wall panel, BRC, hooks, main middle bar, and in situ concrete, are shown in Fig. 8. The shape of the concrete wall in the loop connection was the same as that of the female panel in the proposed connection. The longitudinal bar with a 12 mm diameter should pass through the hooks. After placing this bar, the concrete of middle in situ concrete was cast to complete the connection. The dimensions of concrete wall panels, hooks, main middle bar and locations of hooks in the loop connection are shown in Fig. 8.

3.3 Property of materials

The properties of all the materials used in this study are described as follows.

3.3.1 Steel properties

The properties of steel for both loop connection and U-shaped steel channel connection were identical (ρ=7850 kg/m^3, E=196 GPa, υ=0.3, f_y=240 MPa, f_u=370 MPa and ε_u=0.25).

3.3.2 Concrete properties

The mass density of concrete for both loop connection and the proposed connection was 2400 Kg/m^3 with a grade of B50. The plastic behavior of concrete was modeled based on concrete damage plasticity (CDP) thorium, and the material parameters proposed by Jankowiak and Lodygowski (2005).

3.3.3 Rubber properties

Hyperelastic rubber with three types of test data was introduced to Abaqus to model the behavior of rubber. The U-shaped rubber was used only for the proposed connection and among the steel channels. The mass density of rubber was assumed 1200 Kg/m^3 (SIMULIA 2011).

3.4 Interactions

3.4.1 Loop connection interactions

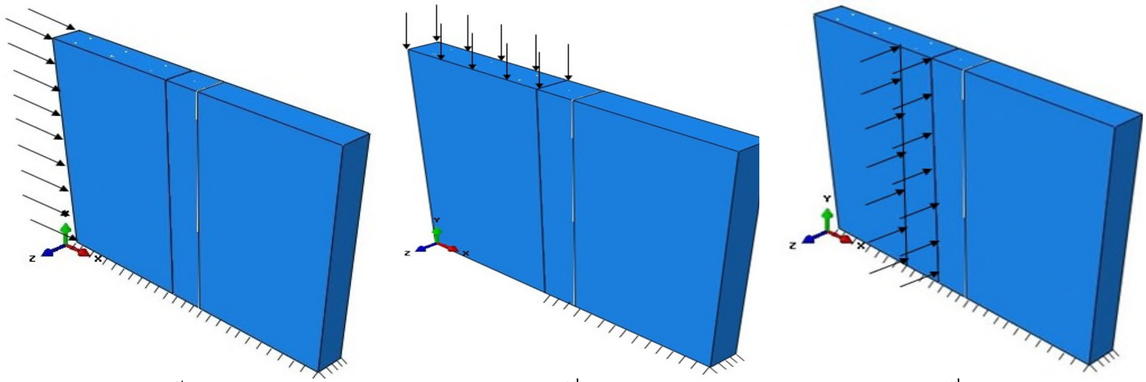
The contact surface of concrete wall panels and the middle in situ concrete constrained with surface-to-surface interaction in the loop connection. Moreover, all reinforcements bonded to concrete with the embedded constraint.

3.4.2 Proposed connection interactions

Surface-to-surface interaction was considered for the contact surface of rubber with steel channels and the outer surface of the bolt with the inner surface of holes in steel channels, as well as rubber and concrete in the proposed connection. In addition, tie constraint was used for the web surface of the male and the female channels with male and female panels and the inner surface of the nut and the outer surface of the bolt.

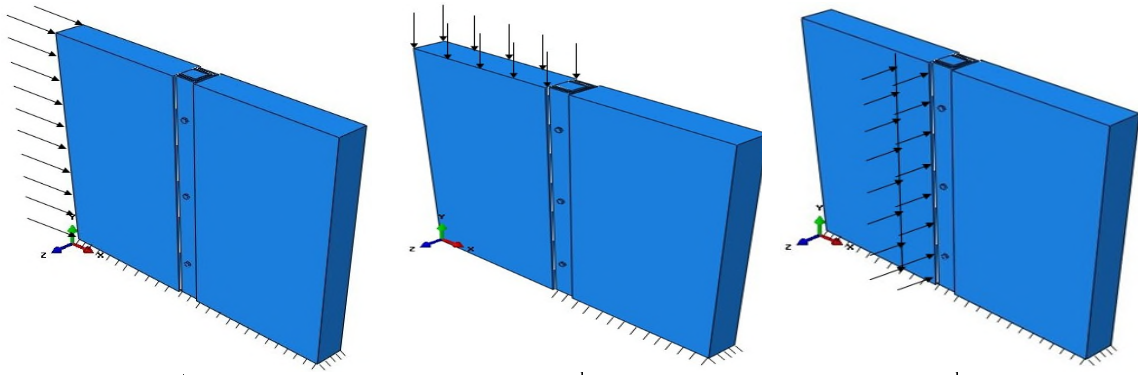
3.5 Load and boundary conditions

Depending on each DOF, the position of loads and boundary conditions was defined. The conditions of panels in buildings were simulated as realistically as possible. The boundary condition for all DOF was determined as a fixed boundary condition, which denotes that all movements in three directions were restricted. However, only the location of the fixed boundary



(a) 1st DOF (b) 2nd DOF (c) 3rd DOF

Fig. 9 Boundary condition and loading in first, second, and third DOF in the loop connection



(a) 1st DOF (b) 2nd DOF (c) 3rd DOF

Fig. 10 Boundary condition and loading in first, second, and third DOF in the proposed connection

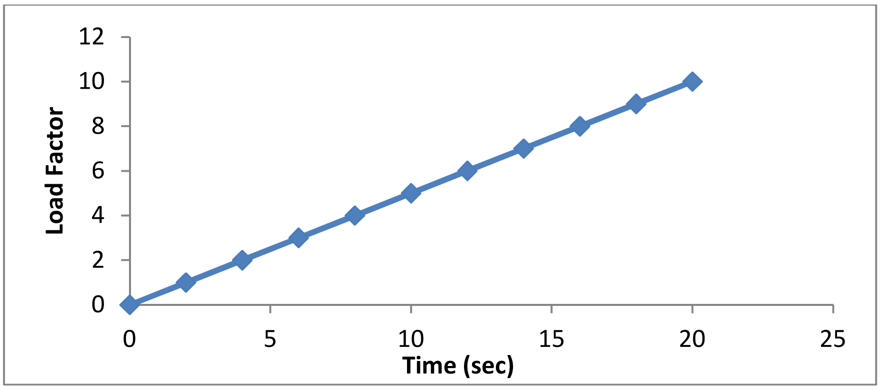
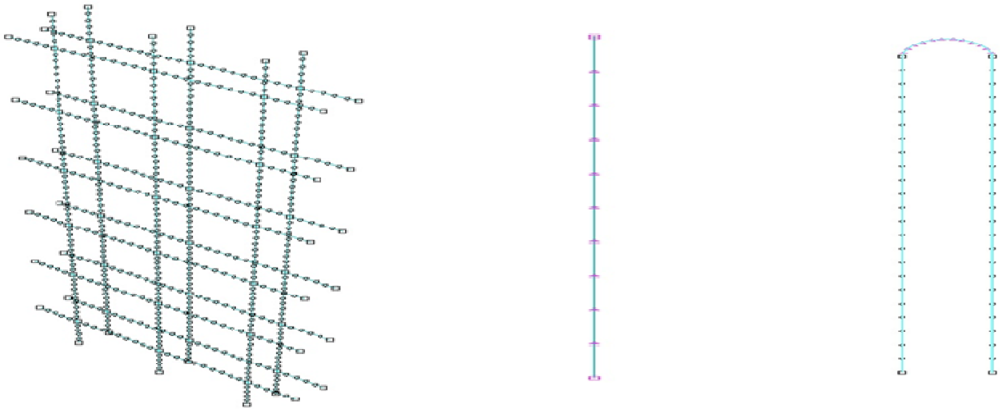


Fig. 11 Monotonic loading for all 3 degree of freedoms

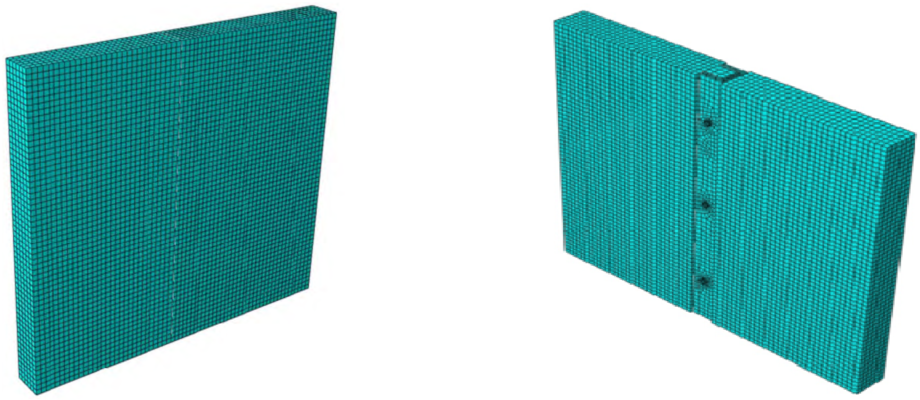
condition was different based on the considered DOF. In the first DOF (displacement in the *X* direction, *Ux*), the bottom of two panels were fixed, and the load was uniformly distributed to the lateral face of one panel for monotonic loading. The second DOF (displacement in the *Y* direction, *Uy*) involved the application of the loading from the top of one panel as uniformly distributed load. The bottom of one panel and the connection were fixed for monotonic loading. An attempt was made to consider the settlement in real condition. In the third DOF (displacement in *Z* direction, *Uz*), the loading was out of plane of walls for the common and the proposed connections. The width of the strip of the loading was equal to the width of the panel, and loading was applied as uniformly distributed load.

Figs. 9-10 show the boundary condition and loading location of first, second, and third DOFs for the loop and the proposed connections. Fig. 11 shows the relationship of time versus load factor for monotonic loading. The magnitude of loading was 5 N/mm^2.



(a) BRC meshing (b) Main middle bar meshing (c) Hook meshing

Fig. 12 Reinforcement meshing



(a) Loop connection (b) Proposed connection

Fig. 13 Concrete meshing

3.6 Meshing

Structured and sweep techniques were conducted to mesh all the components of the aforementioned connections. Fig. 12 illustrates meshing of reinforcement and hooks in the loop connection and in the proposed connection as wire with element type of T3D2.

The type of element used to mesh concrete parts of both connections was the 8-node linear brick element with reduced integration (C3D8R), as shown in Fig. 13.

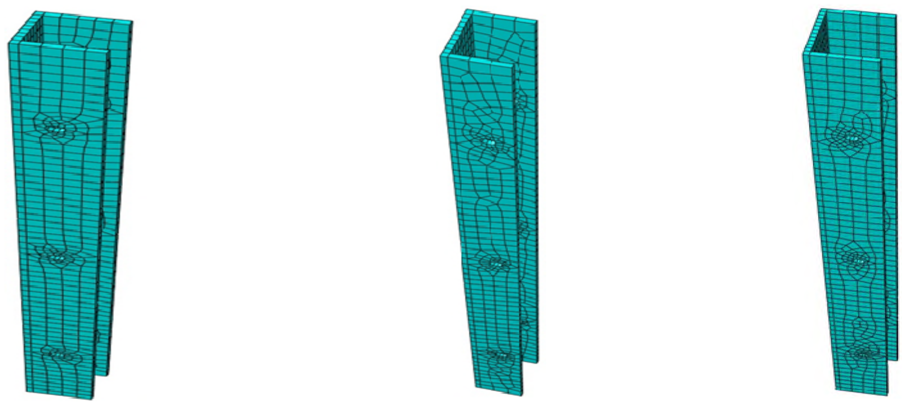
Fig. 14 shows that structured technique and sweep technique were used to mesh the web and flanges of the U-shaped steel channel and the U-shaped rubber, respectively. The type of element used to mesh the web and flanges was the 8-node linear brick with reduced integration.

Bolts and nuts were meshed in Fig. 15 by using the sweep method, and the element type was C3D8R.

As discussed earlier, the main aim of this study is to develop a realistic 3D finite element model to assess the effectiveness of the connection on reinforced concrete frame structures against seismic lateral load.

4. Results and discussion

The contribution of the connection that was subjected to monotonic loading is investigated in this section. A total of six monotonic simulations are performed for this study, including three finite element models of axial force, major and minor shear force DOF for the proposed connection, and the next three finite element models developed for loop connection.



(a) Female Channel (b) Rubber (c) Male Channel

Fig. 14 Steel channels and rubber meshing

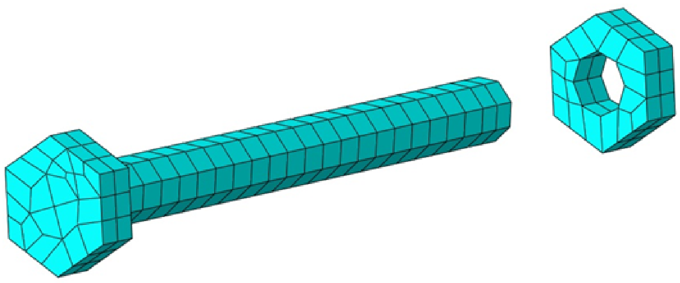


Fig. 15 Screw and nut meshing

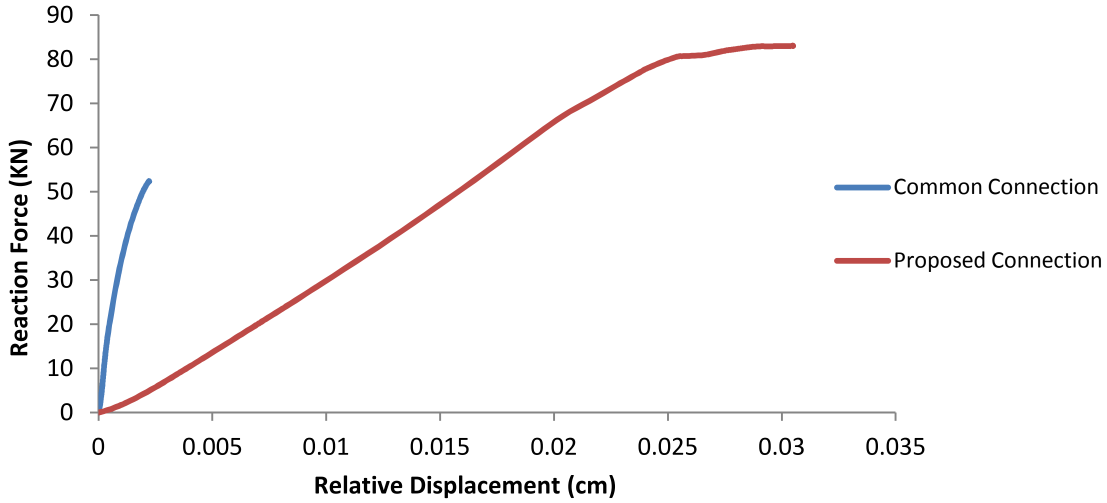


Fig. 16 Pushover analysis of loop/proposed connection subjected to monotonic loading for the first DOF

The loop and proposed connection models in the IBS are ideally constructed based on the accurate representation of the material behaviors of concrete and reinforcing steel. The geometry and material properties of both aforementioned connections are identical. The two data sets for each connection are averaged to determine load-displacement values.

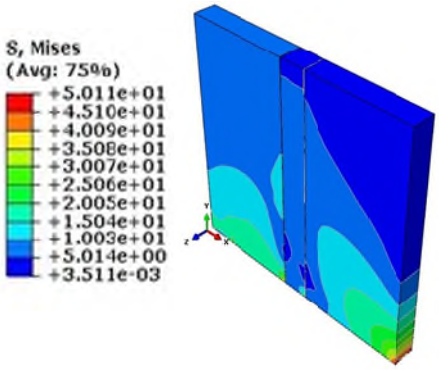
Numerical analysis is conducted to investigate the effect of the lateral displacements on the response of precast wall-to-wall connection. Five key features, including pushover curve, maximum principal stresses, deformation, absolute plastic strain (PEMAG), and concrete damage of both concrete panels and steel reinforcements are considered to determine the effect of incremental lateral movements. Base shear is compared with the maximum relative displacement of the loop connection and the proposed connection for different DOFs (i.e., axial force, in-plane shear force, and out-of-plane shear force). The wall capacity, Fpeak, of monotonic tests is simply the maximum load that the wall could withstand during the loading steps. The displacement of the wall, Δpeak, is recorded as its corresponding loading. The failure load was taken to be 80% of the peak load (Fpeak). According to the maximum load, the walls with the highest strength clearly have the higher load capacity at failure. Displacement at failure is an important parameter to consider, and it is not a function of the ultimate load. Thus, the ability of a structure to dissipate more energy leads to the ability to deform without failure.

4.1 Action to axial force (first DOF)

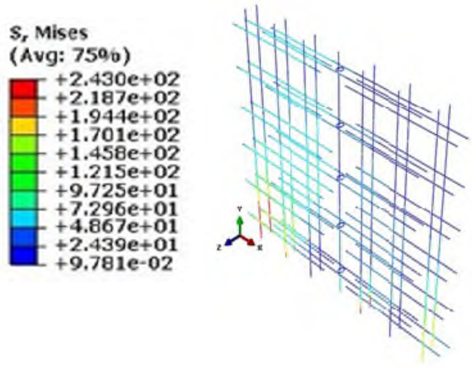
The first DOF represents in-plane axial force that imposes horizontally to the walls, as shown in Figs. 9(a)-10(a).

The relative displacement is determined by subtracting the top left corner point of the left panel and the top right corner point of the right panel from the base shear of the connection curve, as shown in Fig. 16. Based on the relative displacement, the loop connection could resist 52 kN in the first DOF, whereas the proposed connection reached 83 kN.

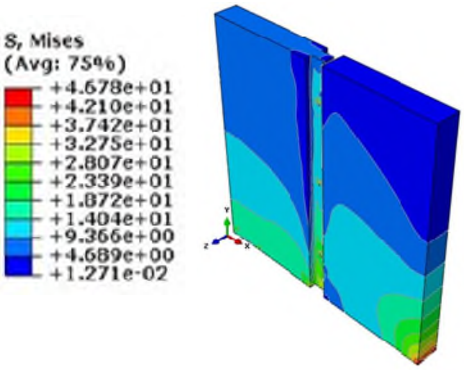
The maximum principal stress distribution on precast wall panels and reinforcements for loop connection is depicted in Fig. 17. Fig. 17 illustrates that the maximum principal stress in loop



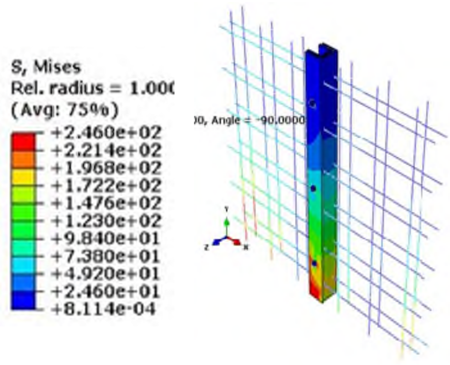
(a) Stress results of concrete in loop connection



(b) Stress results of reinforcement in loop connection



(c) Stress results of concrete in proposed connection



(d) Stress results of reinforcement in proposed connection

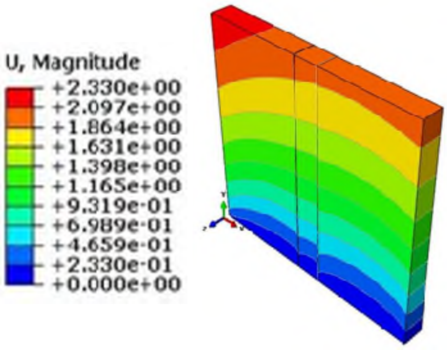
Fig. 17 Stress results of Loop/proposed connection for the 1st DOF (MPa)

connection occurred in the BRC reinforcements in the left panel with approximately 243 MPa. Therefore, the reinforcement is in the plastic range. However, the concrete panels nearly reached their ultimate strength, that is, the maximum principal stress is 50 MPa. Likewise, the maximum principal stress in the BRC reinforcements is approximately 246 MPa and that of the concrete panel is 46.78 MPa for the proposed connection.

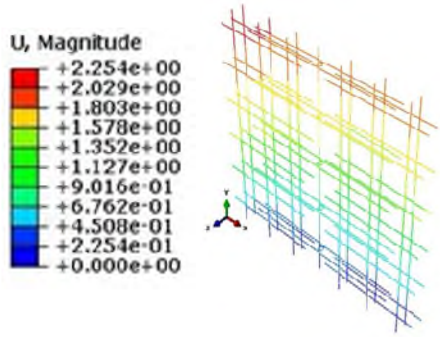
Fig. 18 illustrates the deformation of concrete panels as well as BRC reinforcements in the *X* direction for the loop connection. The maximum deformation observed in the left concrete panel is approximately 2.33 mm.

Thus, the deformation may be caused by the ruptured interface between precast concrete and cast in situ concrete of the connection. However, the maximum deformation of BRC reinforcement is approximately 2.25 mm. The contribution of the proposed connection that is subjected to monotonic loading is investigated in terms of deformation in the connection components and illustrated in Fig. 18, which shows that the deformation of concrete panel and reinforcements is 3.089 and 3.049 mm, respectively.

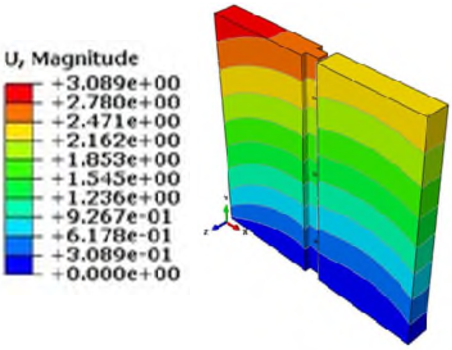
Fig. 19 explains the plastic trend in the concrete panels and in the connections. The graphs demonstrate that the absolute plastic strain in loop connection for the concrete panels is approximately 6.486e-3, whereas the correspondence value for the reinforcement is approximately 5.716e-03. Consequently, the contour results indicate that the absolute plastic strain of the



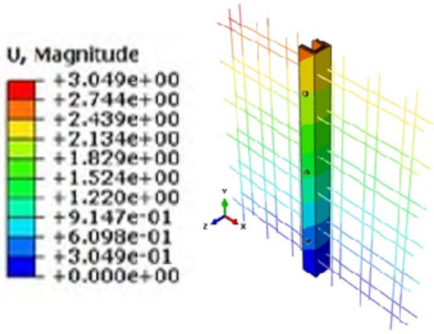
(a) Displacement results of concrete in loop connection



(b) Displacement results of reinforcement in loop connection



(c) Displacement results of concrete in proposed connection

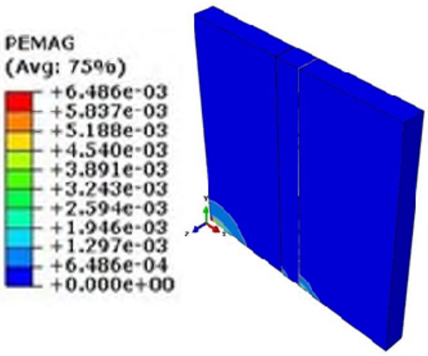


(d) Displacement results of reinforcement in proposed connection

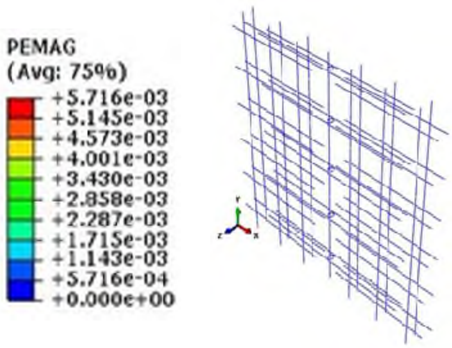
Fig. 18 Displacement results of Loop/proposed connection for the 1st DOF (mm)

proposed connection in concrete panels and reinforcements is 6.737e-3 and 1.152e-2, respectively.

To understand the crack propagations in both connections, the damage in tension, which is represented by DAMAGE-T, is obtained from the results and is shown in Fig. 20 sequentially.

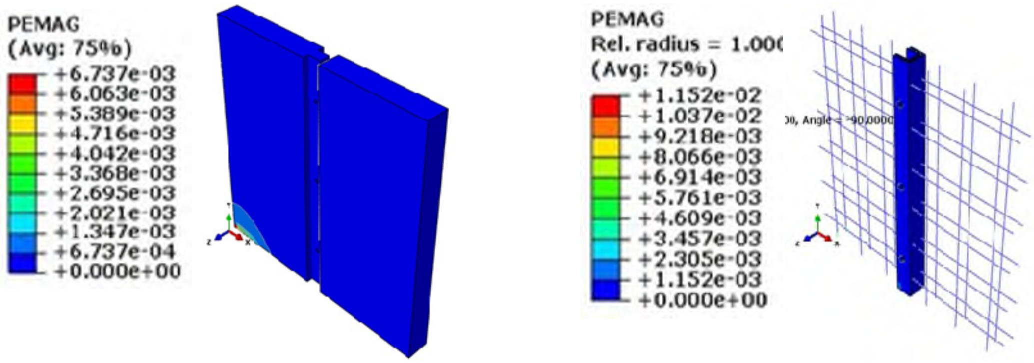


(a) PEMAG results of concrete in loop connection



(b) PEMAG results of reinforcement in loop connection

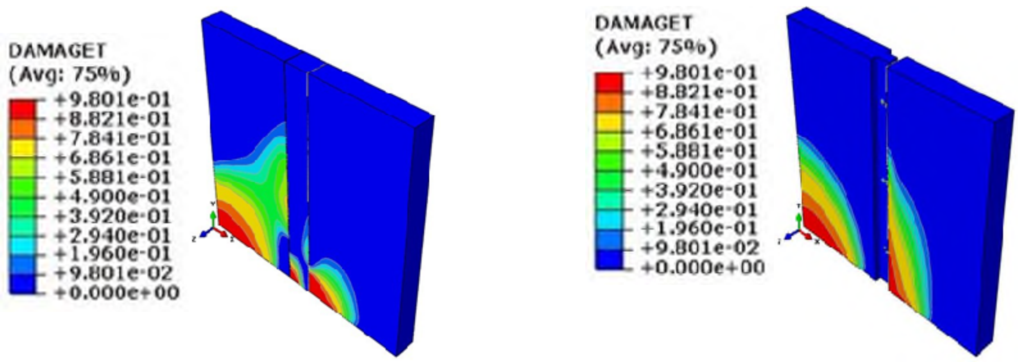
Fig. 19 PEMAG results of Loop/proposed connection for the 1st DOF



(c) PEMAG results of concrete in proposed connection

(d) PEMAG results of reinforcement in proposed connection

Fig. 19 Continued



(a) DAMAGE-T results of concrete in loop connection

(b) DAMAGE-T results of concrete in proposed connection

Fig. 20 DAMAGE-T results of Loop/proposed connection for the 1st DOF

The outcomes indicate that the cracks propagate in both panels, and as expected, the tension damage in the proposed connection took place in fewer positions compared with the tension damage in the loop connection.

Based on the various results from the first DOF, rubber contributes significantly to displacement, stress, plastic strain, and damage in tension.

4.2 Action to in-plane shear force (second DOF)

In this DOF, the force applied in the vertical direction is shown in Figs. 9(b)-10(b). The relative displacement versus base shear curve is shown in Fig. 21. The maximum strength of the loop and the proposed connections, as illustrated in Fig. 21, is approximately 180.5 kN for the second DOF.

Fig. 22 illustrates that the maximum principal stress in the loop connection is in the hooks, with a magnitude of 240.4 MPa. This finding indicates that the hooks are in the plastic range. However, the concrete panels have a magnitude of 31.28 MPa as the maximum principal stress, which is not the ultimate strength of concrete. For the proposed connection, the maximum principal stress for

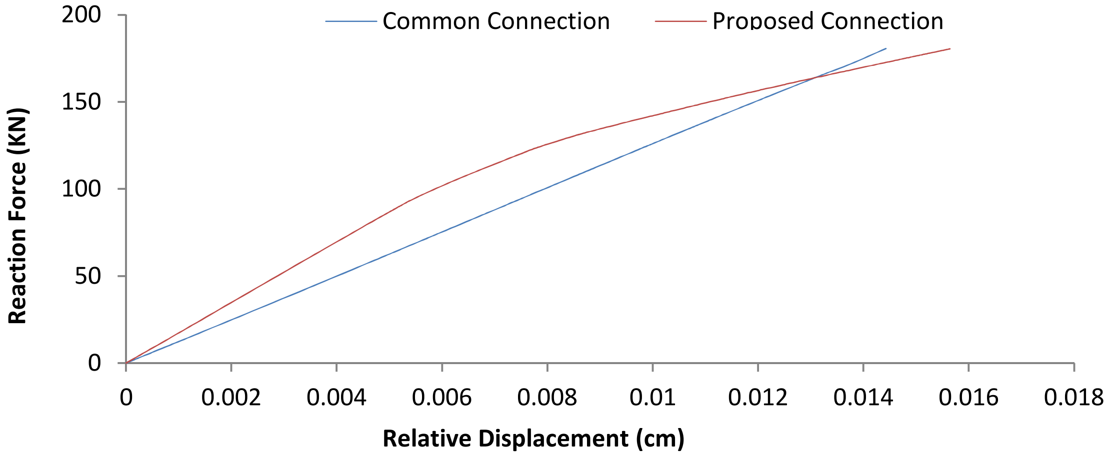
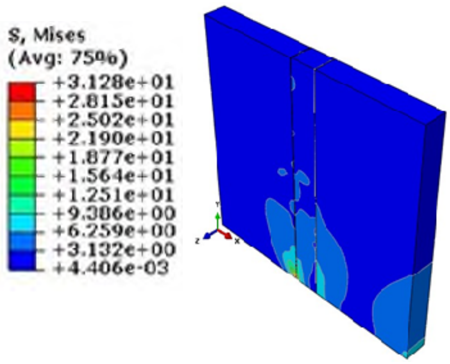
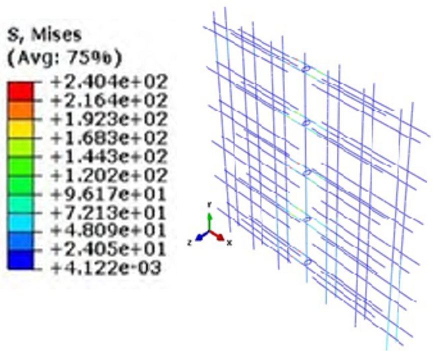


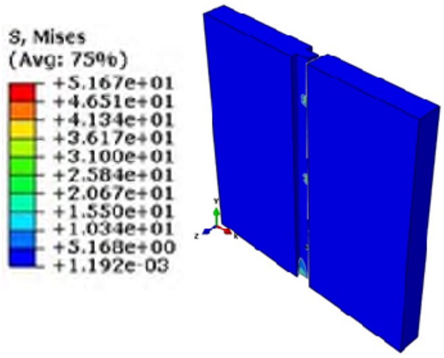
Fig. 21 Pushover analysis of loop/proposed connection subjected to monotonic loading for the 2nd DOF



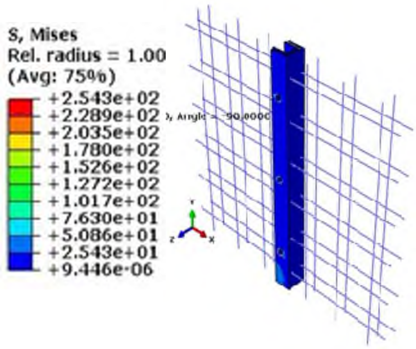
(a) Stress results of concrete in loop connection



(b) Stress results of reinforcement in loop connection



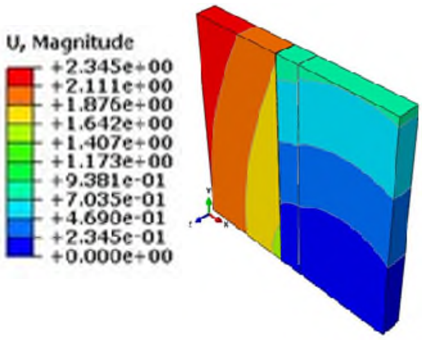
(c) Stress results of concrete in proposed connection



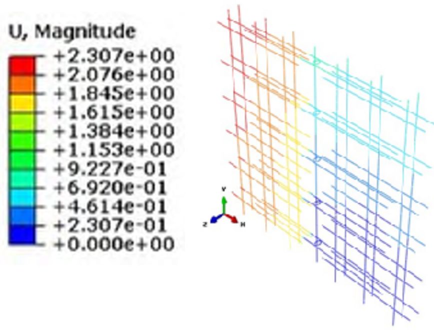
(d) Stress results of reinforcement in proposed connection

Fig. 22 Stress results of Loop/proposed connection for the 2nd DOF (MPa)

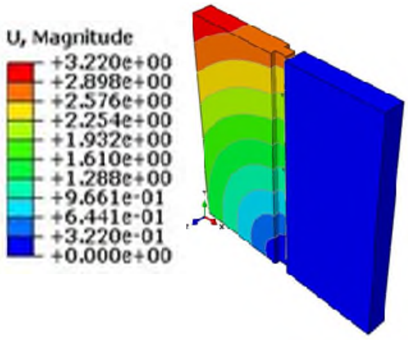
reinforcement and that for concrete panels are 254.3 and 51.67 MPa, respectively, as illustrated in Fig. 22.



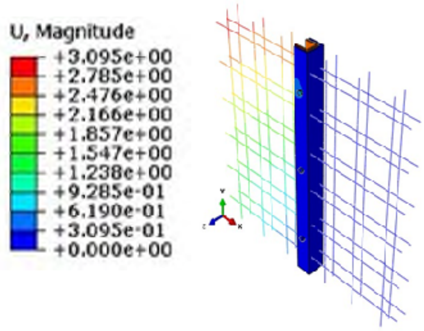
(a) Displacement results of concrete in loop connection



(b) Displacement results of reinforcement in loop connection



(c) Displacement results of concrete in proposed connection



(d) Displacement results of reinforcement in proposed connection

Fig. 23 Displacement results of Loop/proposed connection for the 2nd DOF (mm)

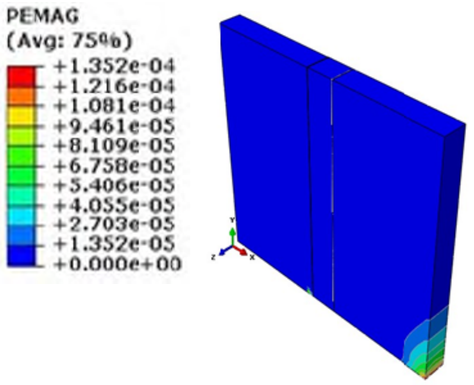
The range of displacement distribution of concrete panels and reinforcement for the loop and proposed connections is shown in Fig. 23. Fig. 23 indicates that the maximum displacement occurs in the left panel for both connections.

The magnitude of displacement is 2.345 mm for the loop connection and 3.22 mm for the proposed connection in concrete. These values are approximately the same for the reinforcement displacement.

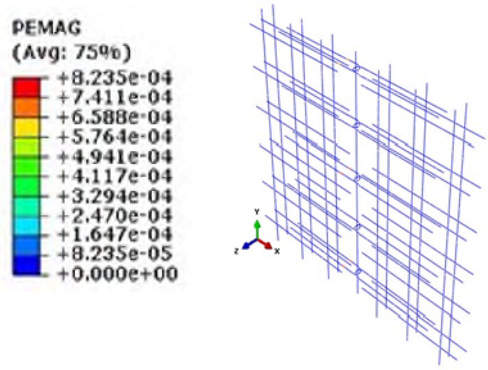
The plastic strain state is determined at any given instance by integration along the stress path and based on the absolute plastic strain (PEMAG). The results in Fig. 24 demonstrate that the plastic trends in the loop connection are in the right corner of the bottom panels and near the holes for bolts for the proposed connection. The magnitude of PEMAG for concrete is 1.352e-4 and 8.235e-4 in the loop connection for reinforcement. However, in the proposed connection, the corresponding value for concrete is 9.719e-4 and 2.963e-2 for reinforcement.

The results reveal that the contribution of rubber is undeniable, particularly when irreversible deformation is considered, where plastic strain in the proposed connection is improved by approximately 40 times.

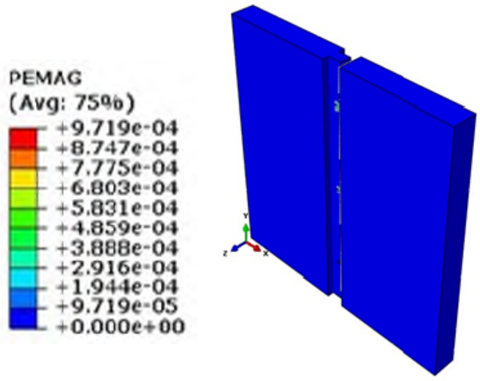
Based on the Fig. 25, the crack propagation caused by tension in the loop connection can be concluded to have occurred at the corner, whereas this kind of crack mostly took place at the hole position in the male concrete panel in the proposed connection.



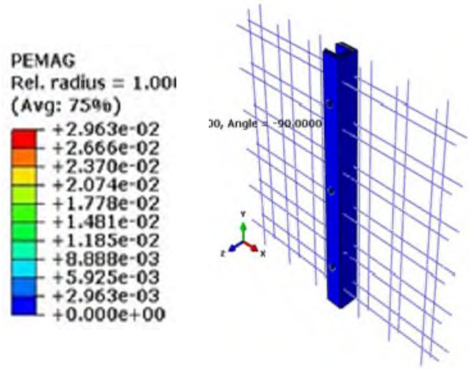
(a) PEMAG results of concrete in loop connection



(b) PEMAG results of reinforcement in loop connection

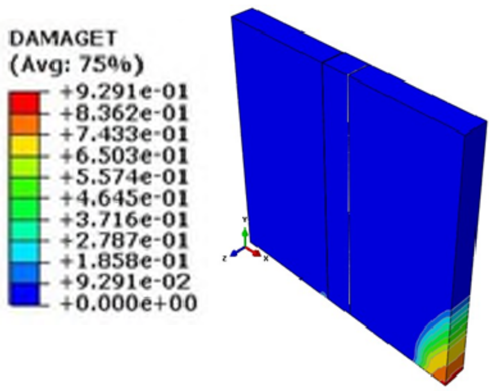


(c) PEMAG results of concrete in proposed connection

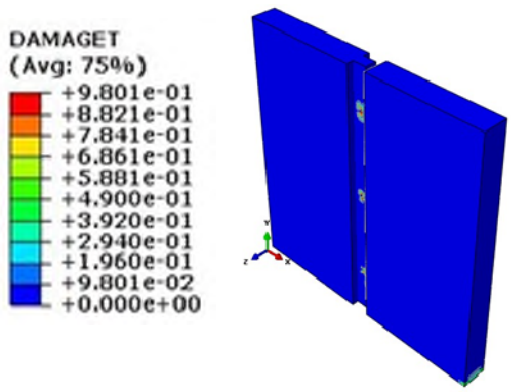


(d) PEMAG results of reinforcement in proposed connection

Fig. 24 PEMAG results of Loop/proposed connection for the 2nd DOF



(a) DAMAGE-T results of concrete in loop connection



(b) DAMAGE-T results of concrete in proposed connection

Fig. 25 DAMAGE-T results of Loop/proposed connection for the 2nd DOF

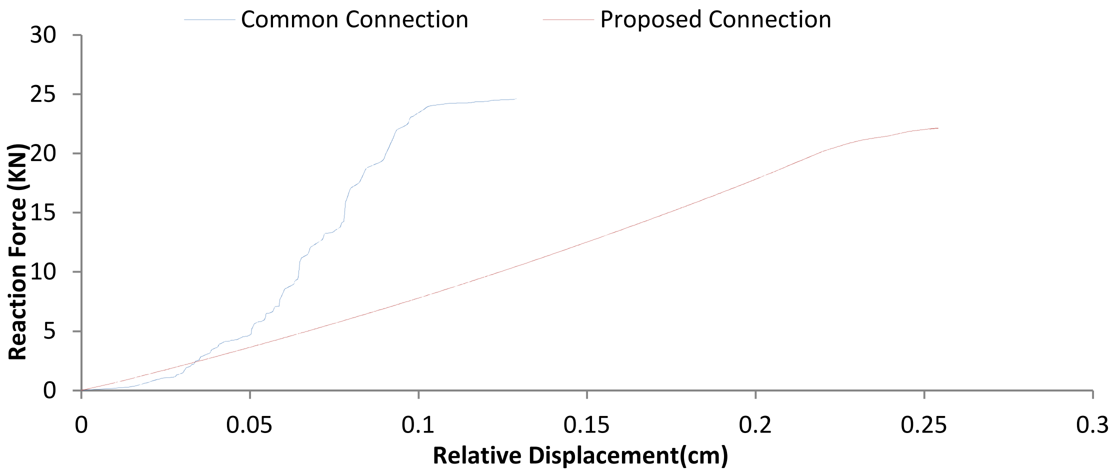
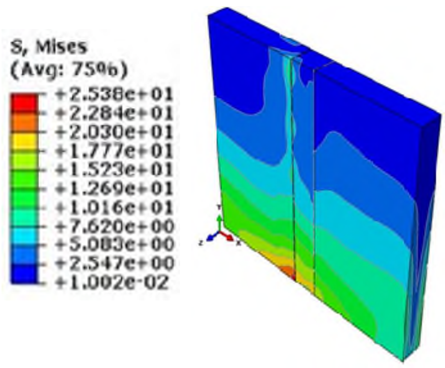
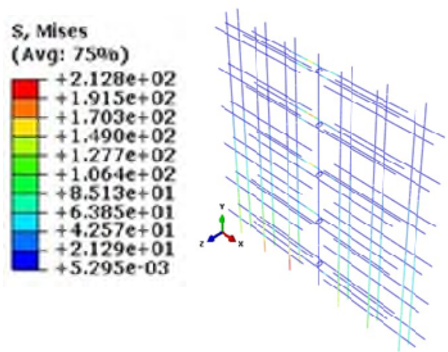


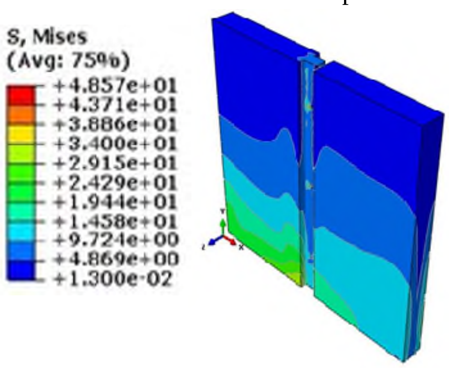
Fig. 26 Pushover analysis of loop/proposed connection subjected to monotonic loading for the 3rd DOF



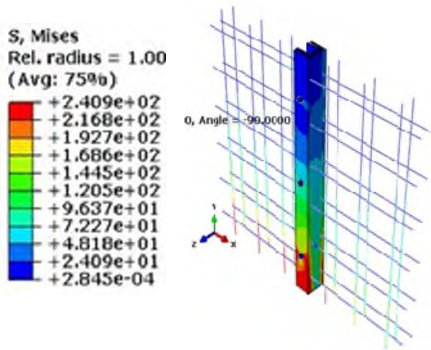
(a) Stress results of concrete in loop connection



(b) Stress results of reinforcement in loop connection



(c) Stress results of concrete in proposed connection



(d) Stress results of reinforcement in proposed connection

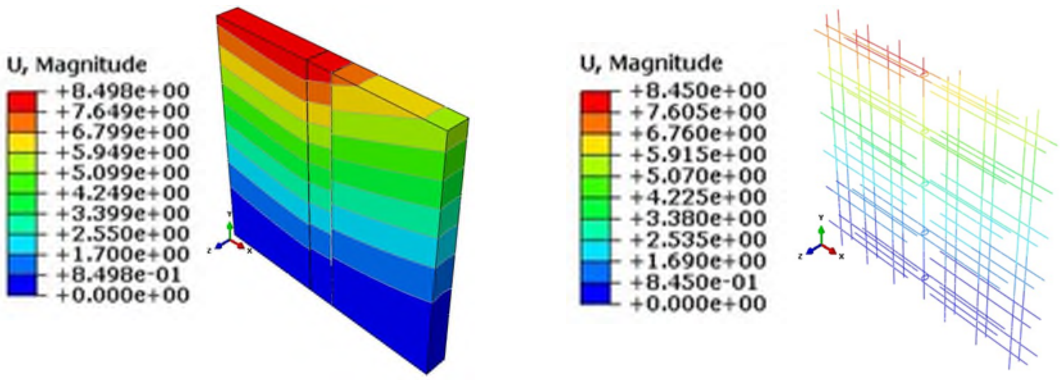
Fig. 27 Stress results of Loop/proposed connection for the 3rd DOF (MPa)

4.3 Action to out-of-plane shear force (third DOF)

In the third DOF, the force applied in the out-of-plane direction is shown in Figs. 9(c)-10(c). The relative displacement versus base shear curve illustrated in Fig. 26 indicates that the loop connection could resist the 24.62 kN force in the third DOF, whereas the proposed connection had an average maximum strength of 22.11 kN in the same DOF.

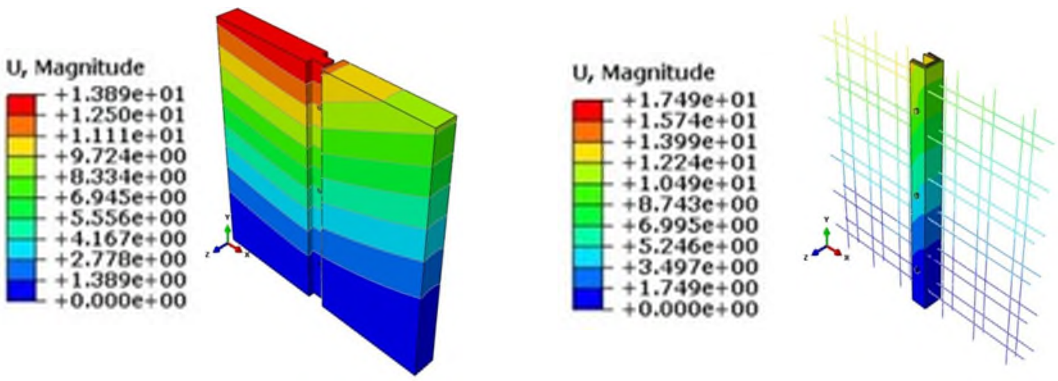
The maximum principal stress in the third DOF is 212.8 MPa for the loop connection and 240.9 MPa for the proposed connection in the reinforcement of panels, as illustrated in Fig. 27. Moreover, the concrete principal maximum stress for the loop connection and the proposed connection is 25.38 and 48.57 Mpa, respectively. The concrete maximum principal stress is approximately close to the ultimate stress in the proposed connection, and the maximum principal reinforcement stress is also in the plastic area for the proposed connection. The maximum principal stress in the proposed connection meets all the reasonable demands imposed on them with respect to yield stress (F_{yield}=240 MPa). As expected, the reinforcements in the proposed connection are in the plastic range. However, the reinforcements in the loop connection remain in the elastic part.

According to Fig. 28, the maximum displacements in concrete and reinforcement in the two aforementioned connections occurred at the top of the connections and the panels. As expected, the



(a) Displacement results of concrete in loop connection

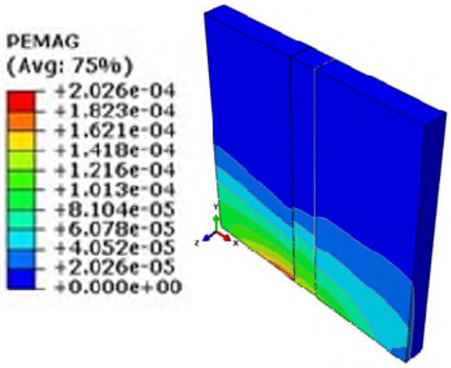
(b) Displacement results of reinforcement in loop connection



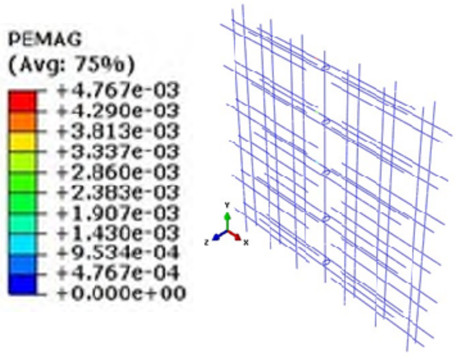
(c) Displacement results of concrete in proposed connection

(d) Displacement results of reinforcement in proposed connection

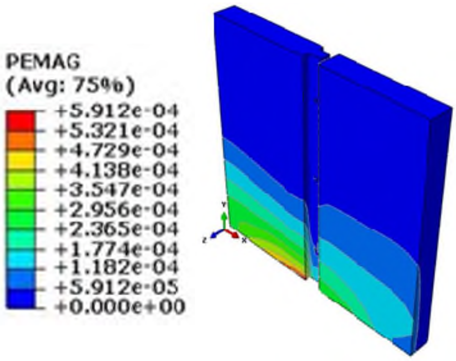
Fig. 28 Displacement results of Loop/proposed connection for the 3rd DOF (mm)



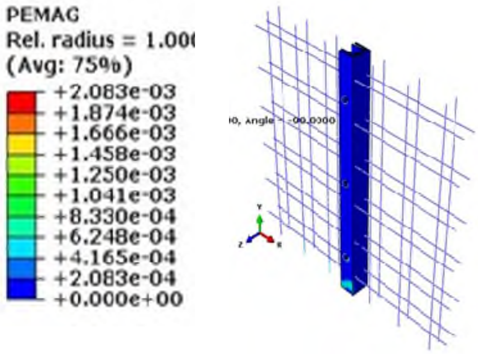
(a) PEMAG results of concrete in loop connection



(b) PEMAG results of reinforcement in loop connection

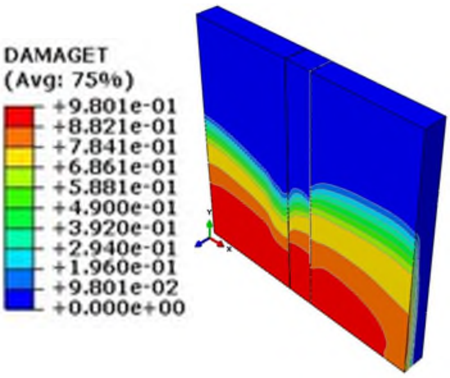


(c) PEMAG results of concrete in proposed connection

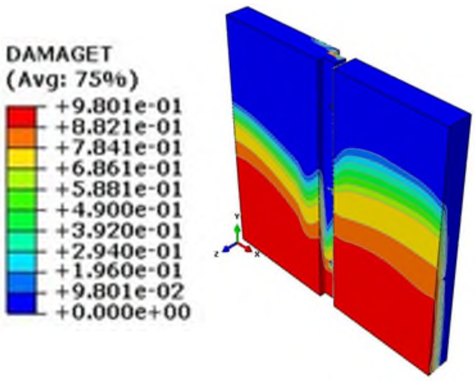


(d) PEMAG results of reinforcement in proposed connection

Fig. 29 PEMAG results of Loop/proposed connection for the 3rd DOF



(a) DAMAGE-T results of concrete in loop connection



(b) DAMAGE-T results of concrete in proposed connection

Fig. 30 DAMAGE-T results of Loop/proposed connection for the 3rd DOF

displacement for the proposed connection is nearly more than twice the displacement in the loop connection because of the existence of rubber in the proposed connection.

Fig. 29 illustrates that the distribution of absolute plastic strain (PEMAG) is nearly the same for the aforementioned connections. Therefore, the loop connection and the proposed connection demonstrate the same out-of-plane reaction.

Fig. 30 illustrates that the damage distribution in tension and tension cracks are nearly the same for the common and proposed connections.

The result indicates that aside from the bolts and the nuts, the rubber between two subsequent steel channels in the proposed connection contributes to load transfer. Nevertheless, rubber has no significant contribution particularly in out-of-plane DOF. Therefore, the same pattern was observed in the distribution of cracks under tension.

Table reveals that the capacity of the loop connection improved from 0.874e-3 (kN.m), 13.063e-3 (kN.m), and 14.99e-3 (kN.m) by approximately 15 times, 30%, and 80% in the proposed connection and reached 14.3e-3 (kN.m), 17.23e-3 (kN.m), and 27.4e-3 (kN.m) in the first, second, and third DOFs, respectively.

Table 2 Capacity of the common/proposed connections in 1st , 2nd and 3rd DOFs.

Kind of degree of freedom	1st degree of freedom	2nd degree of freedom	3rd degree of freedom
	Area under of base shear Vs displacement graph (kN.cm)	Area under of base shear Vs displacement graph (kN.cm)	Area under of base shear Vs displacement graph (kN.cm)
Loop connection	0.874e-1	13.063e-1	14.99e-1
U-shaped steel channel connection	14.3e-1	17.229e-1	27.398e-1
Difference value	13.4e-1	4.166e-1	12.403e-1
Capacity improvement	1533 %	31.893%	82.72%

The graphs reveal that the performance of the wall depends on the connection strength and its corresponding material properties. This finding indicates that the components of connection reach their maximum strength at a certain loading because of the ultimate strength of the material. Consequently, failure for individual components takes place at a different load and displacement. Thus, various parameters must be considered during the analysis.

The connections in this study typically failed when the precast walls either exhibit many cracks or were crushed at the ultimate strength of concrete. When this situation took place, the connection is no longer effectively attached to the wall, and the wall cannot resist any further forces.

Although as discussed in above, the proposed connection showed desired performance when walls are subjected to multidirectional load but there are some drawback for proposed connection as mentioned as follow

1. Due to steel material usage, it needs coating to prevent any corrosion in order to increase the sustainability life of connection.

2. Due to use of rubber or rubber like material in connection, it should be cover by fire preventing material.

3. Further experimental study is needed to be performed in order to evaluate the performance of proposed connection subjected to earthquake excitation.

5. Conclusions

This study proposes a new connection (i.e., U-shaped steel channel) for precast walls. This connection is subjected to monotonic loading. The performances of the loop and the proposed connections are compared to verify the efficiency, high resistance function, and proper action against multidirectional progressive force of the proposed connections. Finite element analysis is further employed to investigate the capacity behavior of the U-shaped steel channel connection.

• The results indicate that strength and displacement were improved in the precast connection that is equipped with the U-shaped steel channel connection compared with the precast connection that used a common approach (i.e., loop connection) when subjected to monotonic load. Hence, the average maximum displacement of all three DOFs in the proposed connection (i.e., U-shaped steel channel) is approximately 70% times greater than the corresponding values in the loop connection.

• Pushover curves reveal that the ability of the loop connection to resist progressive load is considerably less than that of the proposed connection. The capacity of the proposed connection is significant and is approximately 15 times greater than the loop connection capacity for the first DOF. The enhancement is also observed in the second and third DOFs, where the ability of the proposed connection to resist is about 32% and 83% times better than the loop connection.

• Based on pushover graphs obtained from the numerical analysis, the initial stiffness of common connection is greater than that in proposed connection in all translational degree of freedom; however, stiffness degradation also took place earlier in loop connection than U-shaped steel channel connection.

• The proposed connection utilizes the overall connection capacity and correlates well with precast walls because of its high contribution in resisting monotonic load. Accordingly, the cracks are propagated and not concentrated at certain points only. Based on the damage results, the loop and the proposed connections are assumed to have brittle and ductile failure modes, respectively.

Acknowledgments

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