Structural assessment of bolted connections under shear monotonic loading developed for precast concrete walls

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Summary
A novel precast eco-efficient structural wall with high durability was recently proposed. To advance this research, three dry-bolted connections were developed to facilitate the lateral assembly of this wall system. To evaluate the performance of this structural wall system with bolted connections, monotonic shear loading tests were conducted both in-plane and out-of-plane. This paper provides a detailed description of the three bolted connections, the test specimens composed by two walls assembled using the three different connections and the experimental setup. The results from multiple tests are presented and analyzed. Key conclusions are drawn, and practical design recommendations are also provided.

1 INTRODUCTION

Precast structural concrete walls with several configurations have been used for both low and high-rise buildings in many countries with high seismic hazards [1]. Due to the significant in-plane depth of the wall elements, they offer substantial lateral stiffness and the strength capacity [2]. However, the out-of-plane performance of structural walls is usually neglected and can have serious out-of-plane damage [3]. Shear forces in concrete walls are a critical factor in structural design, primarily arising from lateral loads such as wind, earthquakes, or lateral ground pressures. In precast wall-based structures, these shear forces are transferred between precast modules through the joints connecting them [4].

Dry-connections between precast elements does not use wet connecting materials (e.g. concrete) at the assembly stage. Instead, this connection uses mechanical mechanisms, such as bolts or welds, to ensure stability and load transfer between the elements [5]. There are several dry-connections solutions for precast walls, reported in the literature [6], with satisfactory behavior.

Considering the abovementioned, an innovative lightweight structural wall solution has been proposed, with high-durability and lower environmental impact [7]. These walls are composed of two concrete layers: an ultra-high durability concrete (UHDC), and a low cement lightweight aggregates concrete, previously developed [8]. For this specific system, three new bolted connections were designed for the lateral connection between walls (Figure 1) [9].

The main goal of the study herein described is to characterize the structural behavior of those connections under monotonic shear loads. To accomplish this goal, an experimental campaign was developed, with in-plane and out-of-plane tests. The performance assessment was carried out by discussing the shear strength and the failure modes.

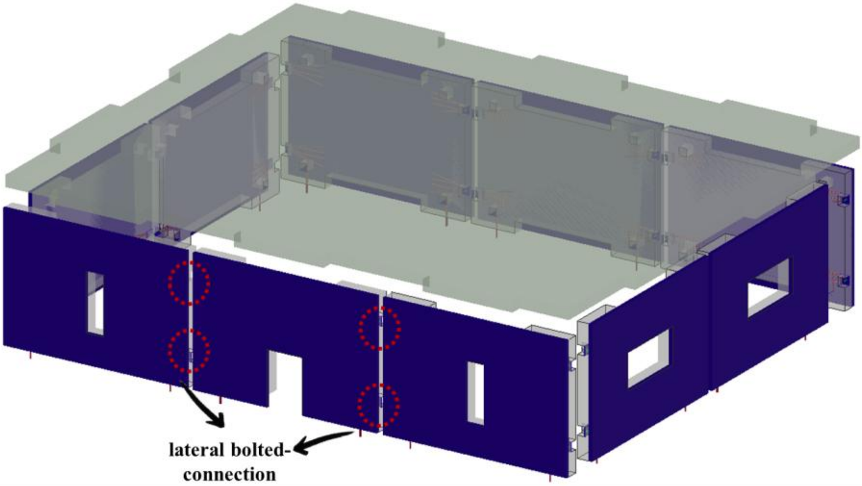
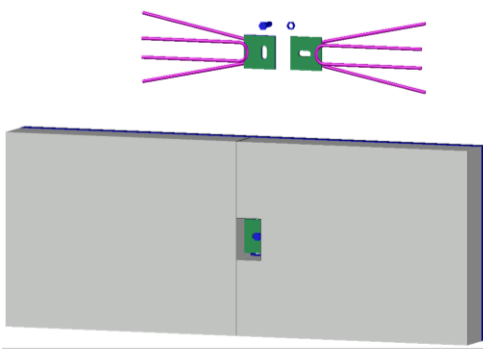


Fig. 1 Proposed composite wall and lateral bolted-connection.

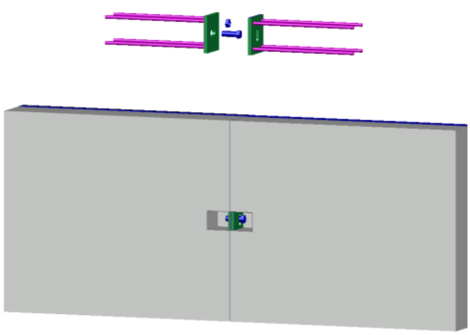
2 DESCRIPTION OF THE BOLTED CONNECTIONS

The three designed connections in this investigation consist of S500 steel plates (dimensions 130×130×12 mm^3), 4∅12mm anchored rebars and high-strength M20 8.8 bolts. The rebars are welded to the stee plate and embedded in the LCLWAC, 400 mm length. Due to the required tolerances during on-site assembly, the steel plates feature ovalized holes oriented in perpendicular directions.

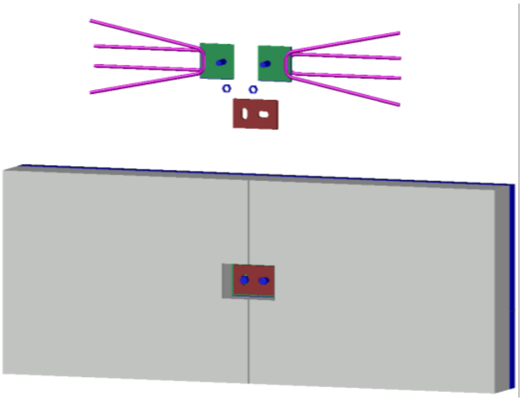
The connections are shown in Figure 2. The Connection-1 have two different sides: (i) one side with the plate inside the wall, and an opening for the assembly; and (ii) other side with the steel plate outside the wall (Figure 2a). The Connection-2 is the same on both sides, with the steel plates in the plane of the wall's cross-section; and the 4 anchor rebars perpendicular; the plates' holes are oriented in perpendicular directions, as abovementioned (Figure 2b). Connection-3 is symmetrical, and the bolt is welded to the plate; the two walls are connected with an extra steel plate, with the ovalized holes (Figure 2c). Connection 1 and 3 have similar anchor rebars' configuration.



(a)



(b)



(c)

Fig. 2 Bolted-connections: (a) Connection-1; Connection-2; and Connection-3.

3 EXPERIMENTAL INVESTIGATION

3.1 Test specimens and set-up

The specimens tested consist of two composite UHDC-LCLWAC walls, connected by the three different connections. The dimensions of each part of the specimen are: 700 mm length; 500 mm wide; 50 mm UHDC thickness and 150 mm LCLWAC thickness. The two layers were reinforced with Ø6//0.10 m A500 ER steel bars and connected to each other by steel trusses. Two types of steel plate were used – smooth and indented surface - to evaluate the friction component between the two plates. The specimens were designed according to the following label: the type of connection (1, 2 or 3); the roughness of the plate (smooth, "S" or indented, "I") and load application (in-plane, "Plane", or out-of-plane, "OPlane"). The geometry of Connection-1 is shown in Figure 3, as an example. In addition, the main concrete properties are shown in Table 1.

The monotonic shear loading was applied using a hydraulic servo-actuator, with a displacement control at a rate of 0.01 mm/s. The load was vertically applied until failure of the wall (Figure 4). Six LVDTs were used to measure the displacements: (i) two horizontal LVDTs; and (ii) four vertical LVDTs. The data was recorded with a frequency of 1 Hz.

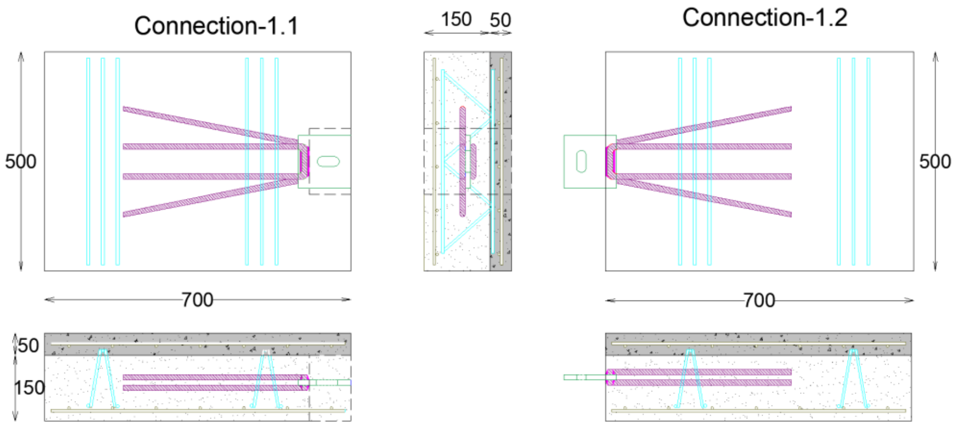


Fig. 3 Geometry of the tested specimen – Connection-1 (dimensions in mm).

Table 1 Material properties, UHDC and LCLWAC [8]

Properties	UHDC	LCLWAC
Compressive strength at 1 day, $f_{cm,cube}$ (MPa)	33.3	24.1
Compressive strength at 28 days, $f_{cm,cube}$ (MPa)	85.7	46.6
Flexural tensile strength at 28 days, $f_{ctm,f}$ (MPa)	6.3	4.3
Splitting tensile strength at 28 days, $f_{ctm,sp}$ (MPa)	4.0	2.2
Young's modulus, E_{cm} (GPa)	49.7	21.6

(a) (b)

Fig. 4 Monotonic shear test: (a) In-plane of the wall; (b) Out-of-plane of the wall.

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 In-plane shear tests

Figure 5 shows the in-plane shear load-displacement curves and the forces/displacement values for first crack, peak strength and ultimate strength. In Connection-1, C1_I_Plane presented higher initial stiffness and C1_S_Plane had high displacement, 15 mm, for a lower load, circa 10 kN, proving the friction effect of the steel plates. However, at the end, the strength capacity of C1_I_Plane was 12% lower than C1_S_Plane. In Connection-2, the strength is supported only by the shear strength of the bolt, due to its configuration. The deformation of C2_I_Plane was 40% higher than C2_S_Plane, showing that the indented plates do not increase the friction component between the plates in Connection-2. Connection-3 had a different shear behavior than the other two. The deformation was 2.3 times higher, caused by the rotation between the two walls.

The crack pattern was also evaluated throughout the tests. In Connection 1 and 3, microcracks were observed near the opening, for values 55-65% of peak load, but with significant rotation of the connection. On the other hand, for Connection-2, no cracks were observed for this load level, showing the benefits of this connection.

In Connection-1, the failure occurred with the detachment of LCLWAC, near the opening, with slippage of the anchor rebars (Figure 6a). In Connection-2 the failure occurred due to the shearing of the bolt, with no significant concrete cracking (Figure 6b). Finally, Connection-3 verified the highest damage. The rotation of the free plate caused the detachment of the LCLWAC, near the opening. However, the failure occurred due to the shearing of the bolt (Figure 6c).

The experimental results were compared with the design shear strength of the used bolts (equal to 118 kN for M20 8.8 bolt) [10]. The average ratio between them is 1.31, 1.29 and 1.37 for Connection 1, 2 and 4, respectively. The results show that the other components of the connection contribute to the shear strength, beyond the bolt.

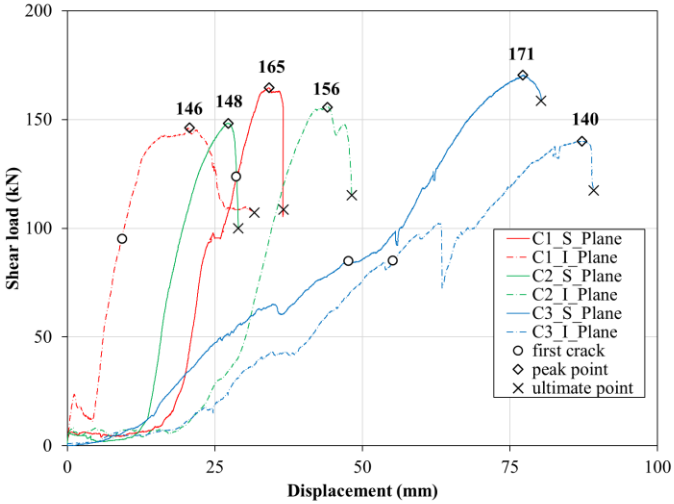


Fig. 5 In-plane shear load-displacement curve and response parameters computed.

(a) (b) (c)

Fig. 6 Crack pattern at failure: (a) Connection-1; (b) Connection-2 and (c) Connection-3.

4.2 Out-of-plane shear tests

Figure 7 shows the out-of-plane shear load-displacement curves with the main parameters measured, like in-plane tests. In Connection-1, after an initial load increase to approximately 35 kN, a significant displacement of around 45 mm occurred under a constant load. This behavior resulted from excessive bending of the plates. High localized forces were applied to the concrete adjacent to the plates, leading to the formation of splitting cracks and concrete crushing (Figure 8a). For Connection-2, the specimen C2_I_OPlane (with indented plates) had a high initial stiffness, compared to C2_S_OPlane. In the configuration of these connections, the shear load applied is supported by the shear strength of the bolt. The transfer of the shear force from the bolt to the plates and then to the anchors rebars causes high stress in the connection (Figure 8b). Connection-3 exhibits the lowest strength capacity among the three connections, albeit insignificantly. The failure occurred due to the plates bending and concrete crushing (Figure 8c).

At the end of the tests, the deformation of the three connections was significantly high, due to the specimens bending.

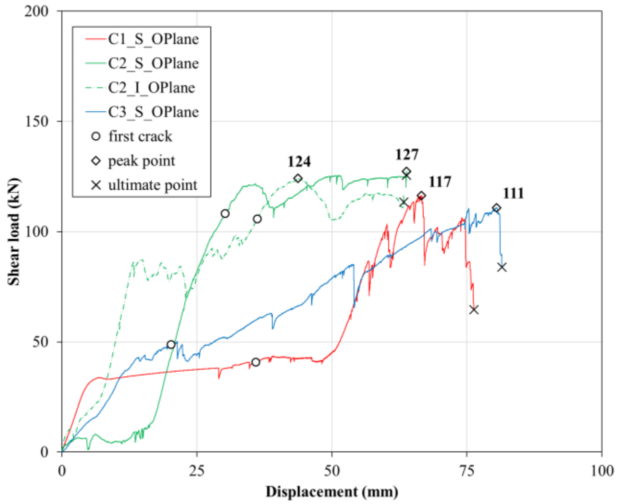


Fig. 7 Out-of-plane shear load-displacement curve and response parameters computed.

(a) (b) (c)

Fig. 8 Crack pattern: (a) Connection-1; (b) Connection-2 and (c) Connection-3.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

In this paper, three innovative bolted connections were developed for a specific wall-based system. These connections feature steel plates with welded anchor rebars, connected using bolts. To assess the structural performance of the connections, an experimental study is conducted, including shear tests in-plane and out-of-plane of the composite walls. The main conclusions are drawn as follows:

- The three connections do not show significant cracks (in-plane shear tests), for loads up to 70% of the peak load.
- In the Connection-1, the indented plates increase the initial stiffness of the connection. Even so, the roughness can be optimized to increase the initial stiffness.
- No significant cracks in Connection-2 were observed, showing the best in-plane shear behaviour, compared to the other connections tested. The failure occurred by shearing of the bolt, circa 152 kN.
- The Connection-3 experiences higher deformations, compared to Connections 1 and 2, circa 2.3 times.
- The connections subjected to out-of-plane shear load have significantly lower strength capacity, compared to in-plane tests, circa 25%.
- Connection-2 show less damage and higher strength capacity than the Connection 1 and 3, in the out-of-plane tests.

This study herein described is part of a comprehensive investigation into the proposed wall and connections, assessing not only the shear behaviour but also the tensile behaviour and cyclic load. Based on the experimental results some optimizations of the connections are needed: (i) optimize the indented plates; (i) increase the dimensions of the plates; and (iii) covering the ovalized holes after walls' assembly. To accomplish this, a parametric study with numerical models will be carried out in the future.

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