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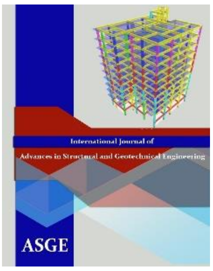

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NUMERICAL MODELING OF RC SHEAR WALLS RETROFITTED WITH UHPFRC

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ABSTRACT

Reinforced concrete (RC) shear walls have an efficient lateral strength and stiffness for resisting lateral forces. Ultra-high performance fiber reinforced concrete (UHPFRC) is a recently developed material with much higher mechanical properties and durability than ordinary concrete. Nevertheless, while extensive studies have shown the superior mechanical and damage tolerant capacities of UHPFRC at the material scale, there remain very few studies on the application of UHPFRC for earthquake-resistant structural elements. Therefore, this study presents the results of an analysis using a finite element (FE) model conducted to predict the behavior of RC shear walls strengthened by UHPFRC jacketing under lateral loading. Firstly, behavior of RC shear wall under lateral loading was investigated with 2D FE model using plane stress element. The FE model results are validated comparing the experimental results in literature. It is shown that the proposed FE model can predict the mode of failure and the behavior of RC shear wall reasonably well. Therefore, the validated 2D FE model is adopted to show the effectiveness of strengthening by UHPFRC jacketing on the overall behavior of RC shear wall under lateral loading. Moreover, based upon the proposed 2D FE model, a comparison between the RC shear walls strengthened by external CFRP sheets and by UHPFRC jacketing was investigated.

Keywords: UHPFRC jacketing, finite element model, RC shear walls, Strengthening, ABAQUS.

INTRODUCTION

In recent years, many of existing reinforced concrete (RC) structures is suffering damages from subjected to severe mechanical or cyclic loading and aggressive environmental conditions. Therefore various seismic retrofitting methods and/or materials based upon performance-based design concepts are urgently needed. During an earthquake, the RC shear walls play a major lateral load resisting system in limiting the seismic damage intensity by reducing the floor displacement [1-3]. A large number of existing low-aspect ratio RC shear walls, with an aspect ratio of less than or equal to 1.5, have low mechanical performances, especially when the elements are built with low strength concrete, have poor reinforcement detailing , designed in accordance with old design codes or have construction faults, and are in urgent need for rehabilitation. Several retrofit techniques employed to improve the mechanical performances of existing low-aspect ratio RC shear walls such as RC jackets [4], externally bonded steel plates [5, 6] or fiber reinforced polymer (FRP) wrapping [7-12], which determine an increase overall structural capacities. The use of RC jacketing usually requires high thickness values higher than 70-100mm, leading to decrease architectural area while increasing total mass of structure. On the other hand, externally bonded steel plates and FRP wrapping have advantages over concrete jacketing method such as much less thickness, lower weight and better constructability. However, strengthening performances are only limited to shear strength and deformation capacity. Axial load capacity can be increased by confinement effect, but is limited in extent. Besides, these methods suffer from disadvantages like low fire resistance, non-susceptibility to bend in the field or corrosion resistance. Recently, UHPFRC have been proposed as suitable material for strengthening of existing RC structures to improve structural resistance and durability. Typical strengths of UHPFRC are of 150 to 200MPa in compression and 7 to 11MPa in tension with high fracture energy [13, 14]. Because of these properties, the use of this material result in improvement of tensile and fatigue performance. Nevertheless, most of the reported studies on UHPFRC focus on the characterization of material properties [15-19], there is very few researchers have used the UHPFRC material as one of the promising and cost effective repair method application (e.g. [20-24]).

In addition to the experimental evaluation of UHPFRC materials and structures, various computational models have been developed to predict the behavior of UHPFRC under external forces. Singh et al. [25] studied experimentally and numerically the flexural behavior of full-scale beams made up of UHPFRC subjected to monotonic loading. They used a non-linear 3D FE analysis model using the FE analysis package ABAQUS [26] to predict the behavior of beams. The concrete damaged plasticity model (CDP) was adopted to model the mechanical behavior of UHPFRC. The model was validated using the experimental results of this study. The results obtained from the numerical models showed that the CDP model can accurately predict the load/moment carrying capacities of the UHPFRC beams. Safdar et al. [13] studied experimentally and numerically the flexural behavior of reinforced concrete beams retrofitted with UHPFRC subjected to monotonic loading. The cracking model is defined through the cracking option in MSC/MARC software. 8-nodes 3D solid elements of type 7 are used for the plate, support, concrete, and UHPFRC. The UHPFRC material models are defined as hypo-elastic material by user-subroutine. The steel reinforcement is idealized using truss elements of type 9. The perfect bond is assumed between reinforcing bar, concrete and UHPFRC. The model was validated using the experimental results of this study. The results showed that the use of UHPFRC in structural elements leads to higher stiffness and to an increased bending capacity. Sadouki et al. [27] conducted a non-linear 2D FE model to simulate the structural response of RC cantilever beams retrofitted with a thin layer of UHPFRC subjected to monotonic loading. The numerical modeling is carried out by means of the FE software DIANA. The smeared crack model was adopted to model the mechanical behavior of UHPFRC. The model was validated using the experimental results in literature.

This study presents numerically the behavior of RC shear wall with 1.5 aspect ratio and low compressive strength (15MPa) tested in [7] in case of strengthening by a UHPFRC jacketing with a thickness equal to 50 mm under lateral monotonic loading. Firstly, the 2D FE model conducted to simulate the behavior of RC shear wall under lateral loading. Element types, nonlinearity material constitutive models were proposed. The 2D FE model results are validated with the experimental data obtained from the literature [7]. It is shown that the proposed 2D FE model can predict the mode of failure and the behavior of RC shear wall well. Therefore, the validated 2D FE model is adopted to investigate the mechanical behavior of strengthened RC shear walls by a jacket consisting of a 50mm UHPFRC layer subjected to lateral monotonic loading under the assumption of absence of slippage at core–jacket interface and perfect bond at footing–jacket interface. The UHPFRC characteristics such as, stress strain behavior under uniaxial tension and compression; and the elastic modules are investigated from literature. Results showed that the strengthening procedure improved diagonal tension shear strength of the reference RC wall having poor concrete quality and confinement. The ultimate resistance of the RC shear wall strengthened by a UHPFRC jacketing is 224%, greater than the ultimate resistance of the original RC shear wall, indicating the effectiveness of the strengthening procedure. Moreover, based upon the proposed 2D FE model, a comparison between strengthening of RC shear wall by external CFRP sheets, which discussed in [12] taking into consideration modeling of the bond surface, and strengthening by proposed UHPFRC jacketing was investigated in terms of the ultimate load and energy dissipation capacity.

FINITE ELEMENT MODELS

ABAQUS software [26] was used to model the RC shear wall and the UHPFRC strengthened RC shear wall under lateral monotonic loading. Brief descriptions of the constitutive models that are used in the model are described below. Displacement control method was adopted to determine the capacity and post-cracking behavior of the considered elements.

Constitutive Models

Concrete and steel reinforcement materials modeling

A "*Concrete damage plasticity model*" (CDP) is used for concrete modeling. This model assumes that the main two failure modes are tensile cracking and compressive crushing [26]. In this paper, the stress–strain relationship for the uni-axial compression proposed by Saenz [28] was used as reported in [29]. The elastic parameters required to establish the tension stress-strain curve are elastic modulus, E_c, and tensile strength, f_{ct}. According to the ACI-318 [30], E_c and f_{ct} were calculated. The fracture energy method was used to specify the post-peak tension failure behavior of concrete as shown in Fig. 4. The steel was assumed to be bilinear elastic-plastic material identical in tension and compression. The bond between reinforcement steel and concrete was assumed a perfect bond.

UHPFRC material modeling

For the UHPFRC material modeling, the same model described in Section of concrete modeling, the "*Concrete damage plasticity model*", is used. In this paper, the behavior in compression is simulated adopting the stress-strain relationship proposed by Graybeal [15]. This model calculates the concrete stresses using equations (1, 2, and 3):

$$F_c = \varepsilon_c E (1-\alpha) \qquad (1)$$

$$E = 3840 \sqrt{fc}\ MPa \qquad (2)$$

$$\alpha = a\ e^{\frac{\varepsilon c E}{b\, fc}} - a \qquad (3)$$

In which, *a* and *b* are calculated 0.011 and 0.24, respectively.

Concerning the behavior in tension, as illustrated in Fig. 1, the uniaxial tensile behavior of UHPFRC is usually consists of three phases: linear elastic, strain hardening and strain softening phase. In first phase, stress is increased linearly without any crack formation because the fibres resist the opening of micro cracks by fibre bridging and UHPFRC keeps taking stress (elastic zone). In second phase, the stress is again increased with the formation of micro-cracks when the fibres starts pull out from the matrix until tensile strength is reached and distribution of small crack is widened (strain hardening zone). As the tensile strength is reached, localized macro-cracks form and propagate in the third phase (strain softening zone). Finally, no more stress is transferred through these localized macro-cracks and final fracture takes place [31, 32]. Because of these properties, UHPFRC has increased resistance against environmental degradation of concrete and high mechanical loading. Thus, UHPFRC is a promising material to significantly improve structural resistance and durability of deteriorated concrete structures. Therefore, according to the outcomes of experimental tensile tests performed on dog-bone specimens and available in literature [25], a proposed FE multi-linear stress-strain relationship can be adopted (Fig. 8).

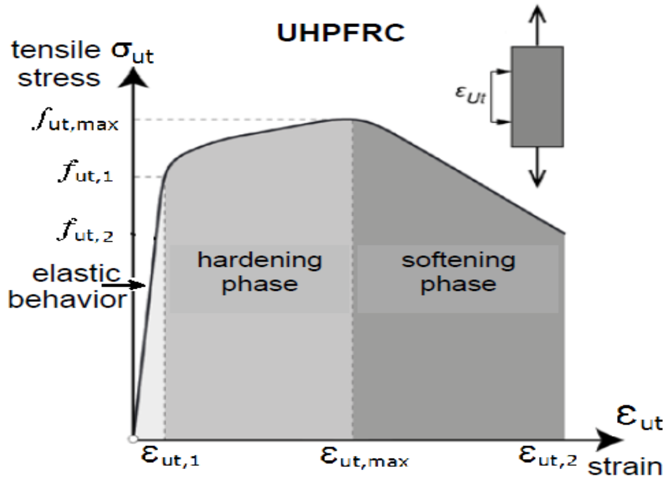


Fig. 1 Characteristic tensile behavior of UHPFRC

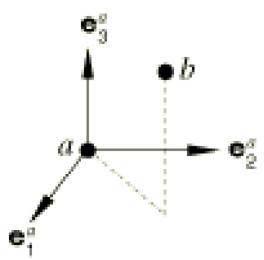
Interfaces between UHPFRC Jacket and Original RC Shear Wall Modeling

Abaqus/standard [26] provides node-to-node interaction method using Cartesian connector element, as shown in Fig. 2(a). Cartesian connector element provides a connector between two nodes that allows independent behavior in three local Cartesian directions that follow the system at node (a).
To define the connection type Cartesian in the present model, the normal and tangential mechanical behavior must be defined. For the normal behavior, one can define spring-like elasticity behavior for the available components of relative motion. In this study, the interface between the substrate concrete surface and the UHPFRC jacket is assumed to be fully bonded. Therefore, it was assumed as a rigid link connecting point (a) to point (b) along a-b direction.

Elements and Meshing

For modeling RC and UHPFRC materials, a 4-node bilinear, reduced integration with hourglass control elements **(CPS4R)** was used. For the reinforcement steel bars, a 2-node linear 2-D truss **(T2D2)** element was used. Fig. 2(b) shows the numerical model geometry. A mesh sensitivity analysis has been performed for evaluating a proper and stable mesh size. As a result, the shear wall is discretized with a square 25 mm side mesh.

(a)



(b)

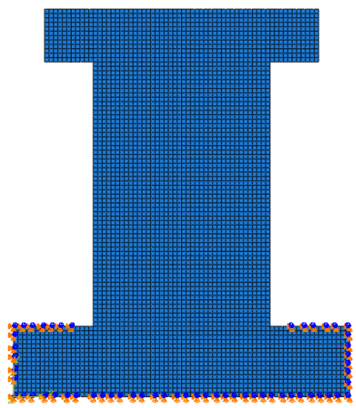


Fig. 2 (a) Connection type CARTESIAN [26]; (b) The numerical model geometry

VALIDATION OF THE PROPOSED 2D NON-LINEAR FE MODEL

In order to validate the accuracy and applicability of the proposed 2D non-linear FE model, it used to simulate the behavior of RC shear wall tested and modeled in [7] and [12], respectively, under lateral loading. Altin et al. [7] presented experimental results on ½ scale five specimens with 1.5 aspect ratio walls. The dimensions and reinforcement (RFT) details of the reference RC shear wall are shown in Fig. 3(a). One of them was tested without any retrofitting as a reference specimen and the rest were retrofitted specimens with CFRP strips. All of the specimens were tested under cyclic lateral loading. Each specimen was loaded laterally as a vertical cantilever with forces applied through the top beam. No axial load was applied to specimens. The test setup, loading system, and instrumentation are shown in Fig. 3(c). During the test, the top displacements and the lateral loads applied to specimen were monitored. The envelopes of lateral load versus lateral drift displacement hysteretic curves for each specimen are given in the reference work of [7].

The reference RC shear wall with low compressive strength was constructed to represent the concrete strength of the existing old buildings. The average compressive strength $\overline{\sigma}_c$ was in the experimental work 15 MPa. E_c and σ_{ct} were then calculated according to ACI-318 [30] as shown in Fig. 4. Poisson's ratio for concrete was assumed to be 0.20. In this study, the concrete is assumed homogenous and initially isotropic. For the steel reinforcement bars, vertical and lateral reinforcement ratios of the wall are ρ_v = 0.0183 and ρ_h = 0.0015, respectively. The elastic modulus, E_s and Poisson's ratio used in the referenced experimental work was not provided, so the elastic modulus for the RFT steel was assumed to be 200 GPa and Poisson's ratio to be 0.3. The yield strength, σ_y and the failure strength, σ_u used in the specimens are listed in Table 1.

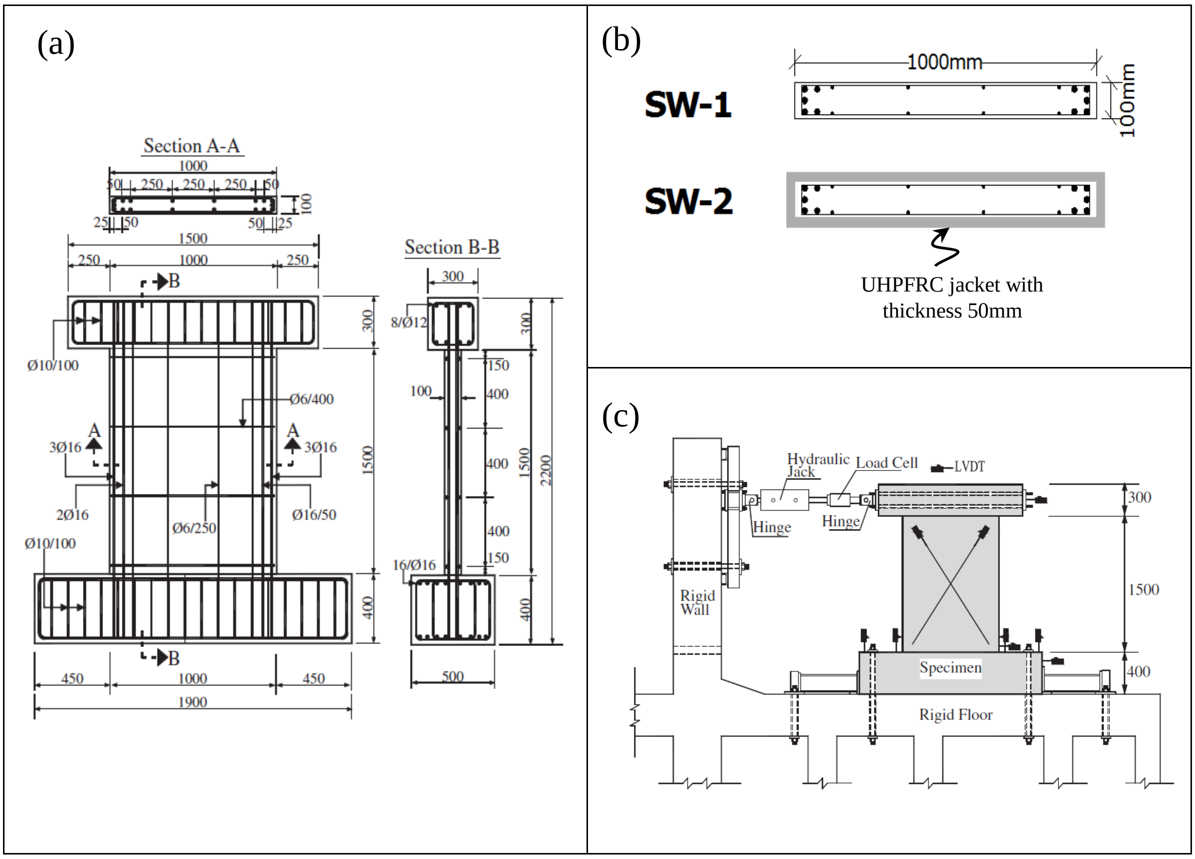


Fig. 3 (a) The experimental specimen in the reference work of [7]; (b) Cross section of SW-1 and SW-2; (c) Test setup and instrumentation of specimen [7] (dimensions in mm).

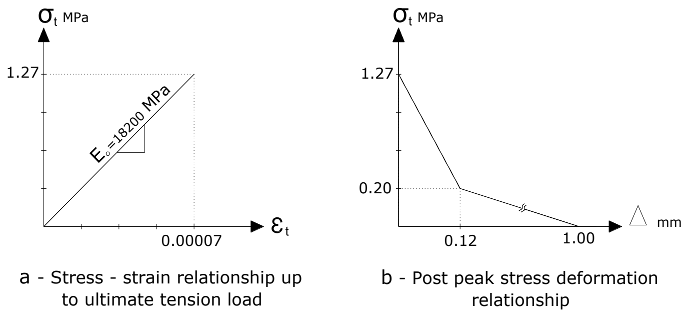


Fig. 4 Concrete behavior for uniaxial tension [28]

Table 1: Properties of reinforcements [7]

Reinforcement diameter	Yield strength σ_y (MPa)	Failure strength σ_u (MPa)	Type
6	325	420	Plain
10	430	522	Deformed
12	428	515	Deformed
16	425	520	Deformed

Reference RC shear wall (SW-1) was failed due to diagonal shear before reaching its flexural capacity. Shear cracks were concentrated through the diagonal of the wall with the increasing lateral load. Fig. 5 illustrates a comparison between the lateral load vs. lateral drift curve of the FE model and the envelope curve obtained from experimental work. As can be seen in this figure, the envelope curve of the experimental specimen can be used for verifying the FE model curve under monotonic lateral load. Also, Fig. 6(a)-(b) illustrate a good agreement of the concentrated shear cracks in one diagonal of the FE model due to uni-direction monotonic lateral loading with one of the two reverse diagonal shear cracks obtained in the experimental specimen due to cyclic loading. The numerical simulation agree well with test results, indicating that the proposed 2D FE model can accurately predict the behavior of RC shear wall under lateral loading.

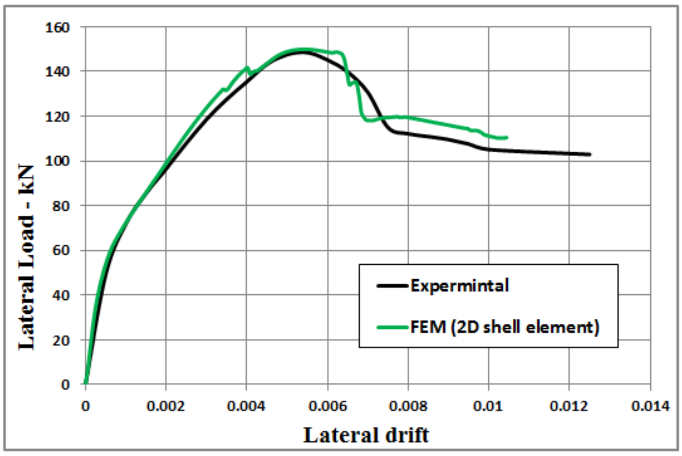
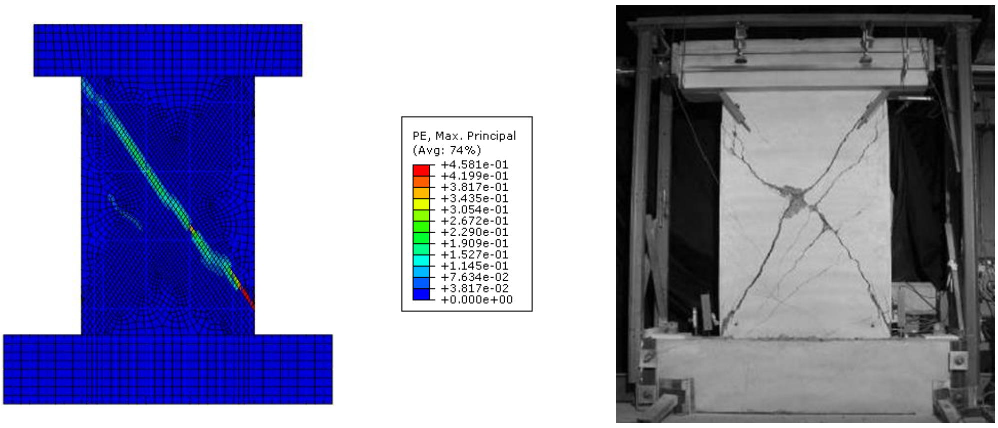


Fig. 5 Lateral load vs. lateral drift for reference RC shear wall (SW-1)



(a) Concrete plastic strain distribution for 2D plain stress model SW-1

(b) Damage pattern for bare RC shear wall [7]

Fig. 6 Mode of failure and crack survey for reference SW-1

STRENGTHENING WITH UHPFRC JACKETEING

“Structural UHPFRC” is UHPFRC, reinforced UHPFRC (or short: R-UHPFRC) and prestressed (or post-tensioned) UHPFRC used for structural applications to enhance structural resistance as full members or as integral parts of (existing) structures in composite action. Structural UHPFRC has the potential i) to improve the resistance and durability of RC structures, and ii) to build UHPFRC structures, a novel generation of structures [33].

In this study, the behavior of the strengthened RC shear walls by a UHPFRC Jacketing can be better understood by making a comparison with the behavior of conventional RC structural walls. Fig. 3(a) displays a conventional RC wall that was taken as a benchmark to assess the behavior of the strengthened RC walls. The validated 2D FE model is adopted to investigate the mechanical behavior of the strengthened RC walls by a UHPFRC jacketing with a thickness equal to 50 mm, as shown in Fig. 3(b), under lateral monotonic loading. The behavior of these walls was predicted using the software ABAQUS [26].

The mechanical properties of UHPFRC material have been conducted by Singh et al. [25]. They studied experimentally and numerically the flexural behavior of full-scale beams made up of UHPFRC subjected to monotonic loading. The experimental and the proposed FEM of UHPFRC material in compression shown in Fig. 7(a), was obtained from uniaxial compression test on cylindrical specimens. The average compressive strength is 143 MPa. The strain corresponding to ultimate strength is 4170 micro-strain and the elastic modulus is 38,470 MPa. The tensile stress strain relationship obtained from the dog-bone specimens is shown in Fig. 7(b). The first cracking occurred at a stress of, $f_{Ut,1}$= 4.6 MPa, which typically corresponds to the cracking strength of the matrix. After first cracking, the fibres resisted the tensile stresses by fibre bridging effect until the peak tensile strength is attained. The fibre bridging results in the formation of micro-cracks throughout the specimen and the material resisted the tensile stresses until the localization of the crack occurs. The average peak tensile strength of the material used in this study is, $f_{Ut,max}$= 5.8 MPa and the strain corresponding to the peak strength is, $\varepsilon_{Ut,max}$= 3300 micro-strain, whereas the softening stage starts and the stress fall rapidly due to the localization of the crack. Fig. 8 shows the proposed FE model of uniaxial tension stress-strain relationship for the UHPFRC. Several studies reported that the bond strength of UHPFRC is greater than normal concrete if proper surface roughness is provided under direct shear test [34, 35]. Therefore, the interface between the substrate concrete surface and the UHPFRC jacket is assumed a perfect bond and there is no sliding at the interface. The pushover curves were computed by increasing the horizontal displacement at the location of the lateral load in order to following the response of the strengthened shear walls.

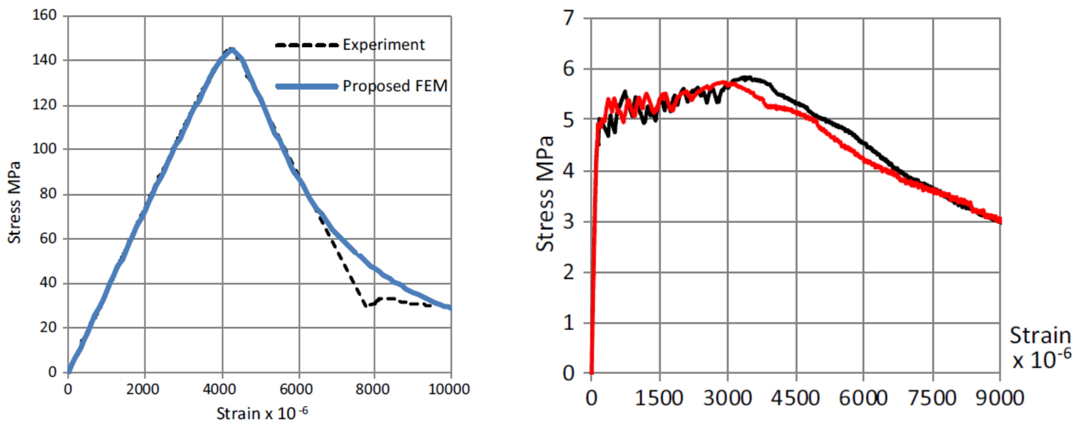


Fig. 7 (a) Experimental and proposed FEM of Compressive stress-strain of UHPFRC; (b) Experimental tensile Stress-strain of UHPFRC under direct tension [25].

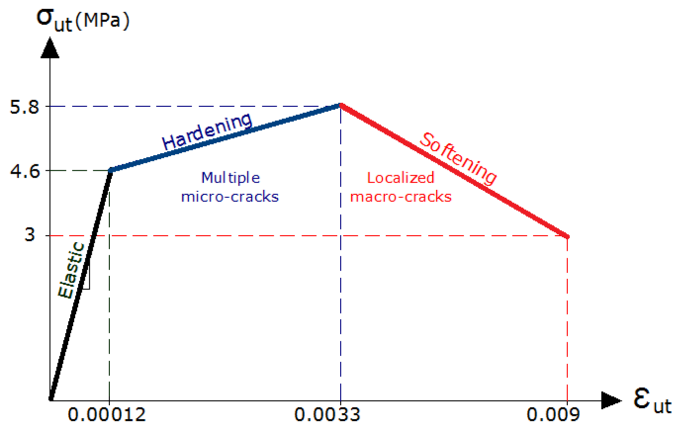


Fig. 8 The proposed FE model of uniaxial tension stress-strain of UHPFRC

Comparison between the structural response of the strengthened specimen by a UHPFRC Jacketing and the un-strengthened specimen are shown in Fig. 9. As can be seen in this figure, lateral load carrying capacity, lateral displacement and energy dissipation capacities significantly increased in the strengthened RC Shear Wall. The ultimate resistance of the RC shear wall strengthened by a UHPFRC jacketing is 224% greater than the ultimate resistance of the reference RC shear wall. Significant shear strength provided by strengthened with UHPFRC Jacketing, prevented diagonal tension shear failure and altered the failure mechanism of specimen. The strengthening procedure showed an excellent ability to control shear cracking. Fig. 10 shows the crack pattern in the critical zone for SW-2; and demonstrates the yielding zones of the boundary vertical steel rebar inner core of RC shear wall. The strengthened shear wall is showed a ductile flexural behavior and at the base of the wall plastic hinge has been developed.

It can be seen at the response of the shear wall strengthened by UHPFRC jacket shown in Fig. 9; the tensile strength of concrete is first overcome in the original wall and later in the UHPFRC jacket, at $f_{ut,\,1}$ = 4.6Mpa. The stiffness reduction is observed when the outer longitudinal rebar of the inner core yields in tension. The stiffness reduces as a result the hardening behavior of the UHPFRC of the jacket. When the tensile strain of UHPFRC reached 0.0033 at drift 0.03%, the UHPFRC material started softening and the lateral load capacity of the wall dropped. All the following deformations occurred in one single horizontal cross-section above the footing leading to high local strains in the longitudinal bars, whereas the plastic hinge occurred in tension when the ultimate strain of the longitudinal reinforcing bars was reached.

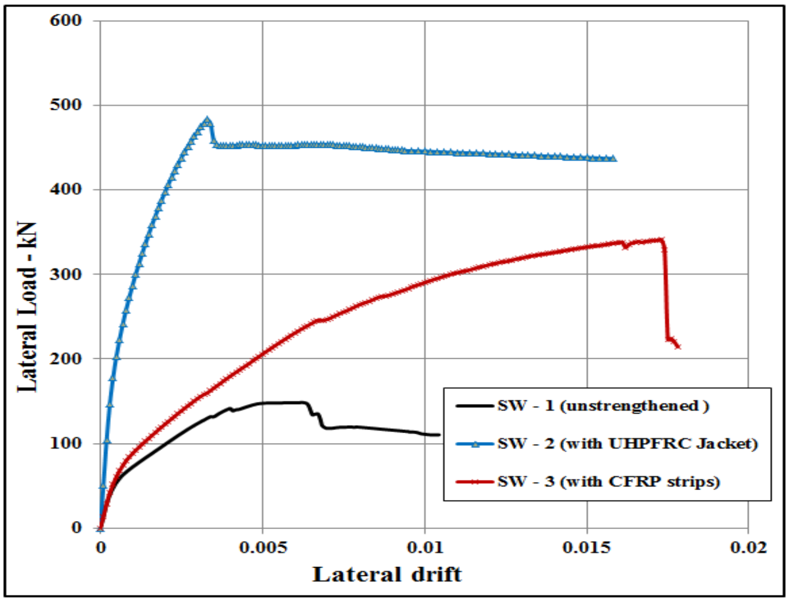


Fig. 9 Lateral load vs. lateral drift for bare RC shear wall

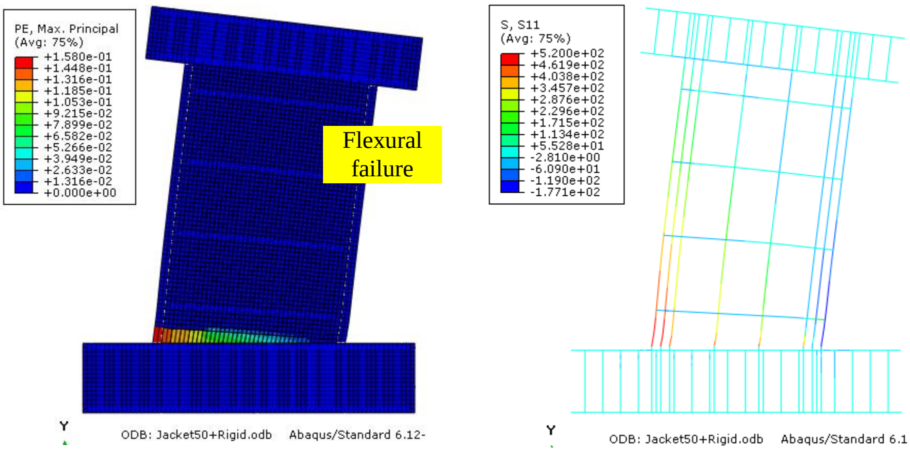


Fig. 10 (a) The numerical plastic strain distribution and; (b) The yielding stress zones for 2D plain stress model of SW-2

COMPARISON BETWEEN STRENGTHENING WITH EXTERNAL CFRP SHEETS AND UHPFRC JACKET

The reference RC shear wall (SW-1) described in [7] reanalyzed in [12] using the proposed 2D FE model in case of strengthened by externally bonded CFRP strips, named SW-3. The modulus of elasticity of CFRP is 231 GPa and the tensile strength is 4100 MPa. The width of CFRP strips is 200 mm and the thickness is 0.12 mm. CFRP strips bonded to original RC wall surface using epoxy resin. The CFRP strips were installed on both faces of the RC shear wall. The modulus of elasticity of the resin is 3.8 GPa and the tensile strength is 30 MPa. The detailed description of applied CFRP strips is given in Fig. 11(a). Element types, nonlinearity material constitutive models for concrete and steel, modeling of CFRP and the adhesive layer between concrete and CFRP strips were discussed in detail in [12].

Fig. 9 illustrates the lateral load vs. lateral drift of RC shear wall strengthened by a UHPFRC Jacketing with a thickness equal to 50 mm (SW-2) and RC shear wall strengthened by CFRP strips (SW-3). There are a significant increasing on the ultimate load, ductility and therefore increasing the dissipated energy when RC shear wall strengthened by a UHPFRC Jacketing. Due to the high strength of UHPFRC material in tension and compression, the UHPFRC jacketing provides a confinement on the existing RC shear walls, which has positive effect on both concrete properties and steel rebar response. The external UHPFRC jacket works as a system of continuous stirrups to resist the effect of shear force and provides the buckling of longitudinal bars. The CFRP strips are not effective on improving the initial lateral stiffness of the CFRP strengthened RC shear wall as shown in Fig. 9. UHPFRC offer a promising solution to structural safety and durability enhancement of existing RC shear walls. On the other hand, CFRP materials have some disadvantages like low fire resistance and high cost.

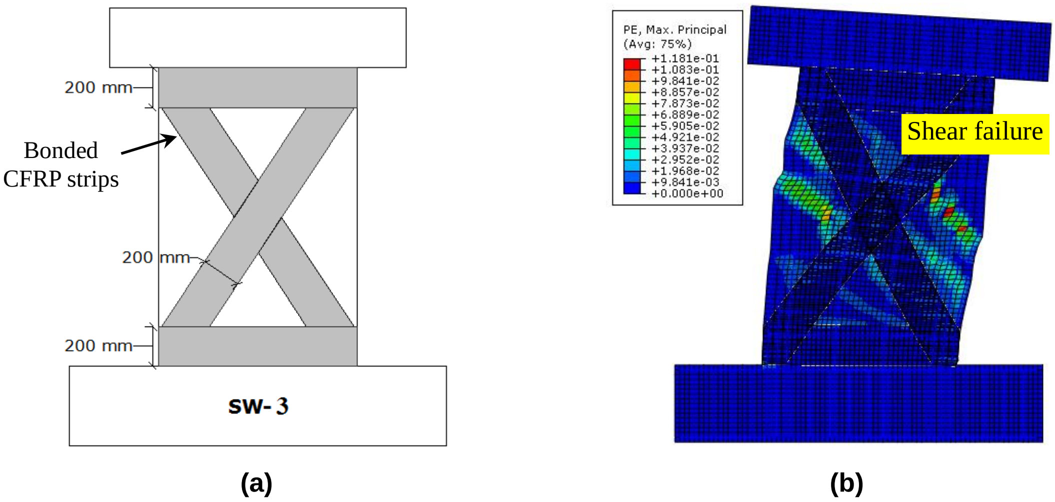


Fig. 11 (a) Description of CFRP strips for SW-3 and; (b) plastic strain distribution [12]

CONCLUSIONS

A proposed 2D FE model for the evaluation of the response of existing RC shear wall strengthened with a UHPFRC jacketing subjected to lateral loading is developed and discussed in thus paper. The application of the numerical model allows highlighting the main advantages of the jacketing with UHPFRC, and gives the possibility to suggest some improvements as follows:

1) The proposed 2D FE model can predict the modes of failure and the behavior of RC shear wall subjected to lateral loading reasonably well.
2) Utilizing the proposed 2D FE model results showed that, the proposed UHPFRC improved diagonal tension shear strength of the reference RC wall having poor concrete quality and confinement.
3) The ultimate resistance of the RC shear wall strengthened by a UHPFRC jacketing is 224%, greater than the ultimate resistance of the original RC shear wall, indicating the effectiveness of the strengthening procedure.
4) Comparing with strengthening by lateral CFRP strips, the strengthening by a UHPFRC Jacketing which is characterized by high strength, ductility, durability and fracture toughness is the best. The external UHPFRC jacket, works as a system of continuous stirrups and provides a confinement on the existing RC shear walls.
5) Finally, the numerical model highlights how the behavior of RC shear walls can be further improved, if the jacket is better connected to the footing.

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