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Numerical simulation on the square column's strengthening characteristics utilizing the SCC jacketing

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Abstract. This research aims to simulate and investigate the efficiency of strengthening damaged concrete columns using concrete jacketing. The numerical program included unjacketed reference column made of ordinary RC concrete had a cross-sectional dimension of (100×100) mm and 560 mm long reinforced concrete. These cores were damaged by loading them with approximately 60% of their actual ultimate load capacities as a service load. Then, column specimens were strengthened by applying two types of self-compacting concrete SCC jacketing, which were 25 and 30 mm thick, on all four sides. Exposed to external loads at different directions vertically and horizontally simulate to the seismic load. The 3D Finite Element (FE) simulation is used to predict of three structural criteria that were selected and evaluated (deflection, stress, cracks). The results show that the failure of the strengthening columns is interesting and corresponds to the characteristics of the cracks formed in the concrete section, which was documented numerically using 3D Finite Element (FE). A significant improvement of deflection has been noted at the values at the top SECTION of columns compared to the reference sample reaching an average of up to 36.6% when using a 25 mm thick SCC-3500 jacket.

Keywords: ANSYS (FE); concrete columns; earthquake simulation; SCC Jacketing; strengthening

1. Introduction

Many of the concrete buildings still standing in Syria have had their lifespans, or operational lives, shortened as a result of issues with deterioration, partial deconstruction, and destruction. In addition to the earthquake catastrophe (Patel *et al.* 2022), there is a general deficiency of funding for the replacement of obsolete infrastructure with modern facilities (Tawashi *et al.* 2019). So that to increase usable life, the maintenance, proactive strengthening, and corrective measures are still necessary.

According to (Tayeh *et al.* 2019), maintaining and strengthening the structural components is essential in today's world. Due to the notable advancements in strengthening materials (Mercimek *et al.* 2021), , the variety and variances among them, and the notable rise in cost, many countries are now dependent on fixing structural elements and self-reliant on the production of the necessary

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materials. in more ancient buildings or those that have experienced seismic activity or external shocks and explosions. One has to be interested in better building materials and knowledgeable of strengthening subjects in order to carry out the consolidation and reform process in the future. Since data on how effectively the structural system performs following reform throughout the operational phase, as well as data on the supposed extension of the service life (Tawashi *et al*. 2019, Patel *et al.* 2022), this must be assessed prior to the necessary strengthening of the structural component, as the goal of the strengthening will determine the best course of action for extending the operational life of the concrete elements, whether the goal of the strengthening is to protect and manage the damage caused by the destruction, to raise the structural efficiency of the members, or both at the same time.

The column is a basic structural component and the main pillar for the structural system's integrity since it carries loads from slabs and beams to the foundations. Columns in structural structures may be vulnerable to natural calamities such as earthquakes (Altun *et al.* 2003), fires, and so on. Such conditions may render columns unable to bear applied stresses. As a result, these columns must be strengthened in a variety of ways, including wrapping CFRP laminate, NSM with steel bars, the jacketing technique, reinforcing with steel strip ties, or a combination of some of these techniques (HELLES, Arafa and ALQEDRA, no date). There has been an increase in the number of studies on various approaches for reinforcing concrete buildings. Numerous studies have shown that adding a concrete jacket to structural concrete elements, such as square reinforced concrete (RC) columns, can significantly increase their ultimate load-carrying capacity and ductility (Tayeh *et al.* 2019, Mabrouk *et al*. 2022, Tahzeeb *et al*. 2023), Despite multiple studies, the bulk of them neglected to consider the use of low-cost, locally manufactured self-compacting concrete as a jacketing material.

Self-compacting concrete (SCC) is one of the most significant technical developments in the concrete and construction sectors right now (Tawashi and Alamoudi 2023). Because of the high workability of self-compacting concrete, its employment in structural building and element strengthening has expanded significantly in recent years (Okamura e*t al.* 2003, EFNARC 2005; Mohammed 2020, Tawashi and Alamoudi 2022a). SCC is known as a green construction material and high-flow concrete since it can spread out from a pumped place, fill a model, and encapsulate reinforcing steel without the requirement for human or mechanical compaction (BülentÇelik 2017). SCC stands out for its superior characterization and cheaper construction costs when compared to alternative strengthening materials (Harkouss and Hamad 2015, Eid *et al*. 2017, Tawashi and Alamoudi 2022b), SCC stands out for its superior characterization and lower construction costs as compared to other strengthening materials.

The optimum strengthening procedures are determined by the type of structure being reinforced and the type of stress applied to it. Increased flexural and axial compressive strength is more significant for structures exposed largely to static stress, whereas increasing flexural and shear strength is more critical for structures subjected primarily to dynamic load. Strengthening can also be used to adjust the stiffness and ductility of the column. Minor cracks without damaging the reinforcement, surface concrete damage without impacting the reinforcement, concrete crushing, reinforcement buckling, or ties rupturing can all occur in an RC column. Depending on the degree of the damage, techniques such as injections, removal and replacement, or jacketing may be performed. In construction, the RC columns are strengthened using four jacketing procedures that are often used (Kaushal *et al*. 2022):

- A lightweight cage of reinforcement with concrete jacketing.
- Steel sheath.
- Composite material jacketing (CFRP).

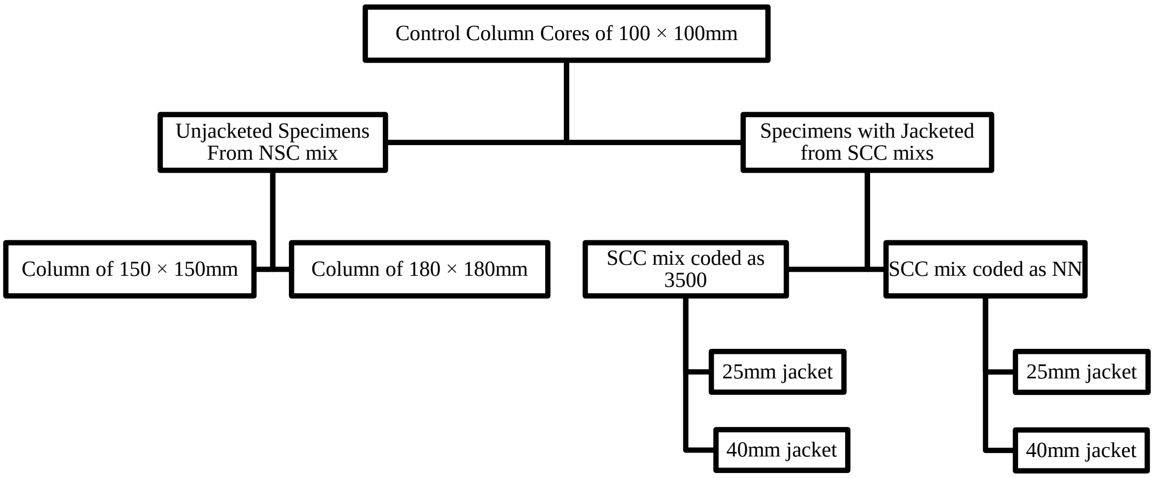


Fig. 1 Numerical Program

- Jacketing of precast or pre-stressing concrete.

Several experimental studies on damaged and undamaged typical vibrated concrete columns showed the effectiveness of these procedures. Additionally, extensive numerical studies were used to model the findings of experiments or to research new factors that couldn't be studied experimentally. In this research a numerical simulation using ANSYS FE has been conducted to investigate the behavior of strengthened columns to have a preview on the effectivity of this simple strengthen method which has used in the affected-war RC columns.

2. Review of literature

Mabrouk presented research on the effects of employing ferrocement jackets to reinforce short columns. Under axial loading, 14 short, square columns with identical diameters were tested (Mabrouk *et al.* 2022). One column served as the control. The remaining thirteen specimens were reinforced with ferrocement while varying the type and number of layers on the specimen. It was discovered that the average strength of columns rose from 11 to 40% when ferrocement was used as a reinforcing technique. The use of ferrocement jackets for reinforcing concrete columns was then further evaluated using a finite element analysis on the tested column specimens. To determine the capacity of short square columns reinforced with ferrocement jackets.

A numerical investigation on the structural behavior of partly loaded square SCC short columns strengthened in different ways, including CFRP wrapping and near-surface mounting with steel reinforcement bars (hybrid technique), was given by Hassan *et al*. (2020). The numerical study extensively explored a variety of parameters, including the impact of more CFRP layers, the impact

Table 1 Details of Column Specimens

Type#	Specimens	Notation	Column core (mm)	Total cross section (mm)	Jacket Thickness (mm)
1	Control Column Core	UC*	100 ×100		-
2	Specimens Jacketed from NSC mix	NSC	100 ×100	150 ×150	25
3	Specimens Jacketed from NSC mix	NSC	100 ×100	180 ×180	40
4	Specimens Jacketed from SCC mix	3500	100 ×100	150 ×150	25
5	Specimens Jacketed from SCC mix	3500	100 ×100	180 ×180	40
6	Specimens Jacketed from SCC mix	NN	100 ×100	150 ×150	25
7	Specimens Jacketed from SCC mix	NN	100 ×100	180 ×180	40

*UC: Unconfined columns; 3500, NN: SCC two jacketing types

of different compressive strengths, the impact of different beginning loading ratios, and the impact of different CFRP strip counts. The convergence in the values of the ultimate load and maximum displacement values demonstrated that the numerical research and the experimental work had a very good agreement. Additionally, the specimens were reinforced with complete CFRP wrapping, and a hybrid specimen had active layers of CFRP laminate. As the column's compressive strength rose, the same result was seen. The strength capability of the columns was reduced as the loading ratio increased. On the other hand, reducing the distance between two consecutive laminates increased the sample's enhanced partial wrapping with CFRP laminate's ultimate load capacity.

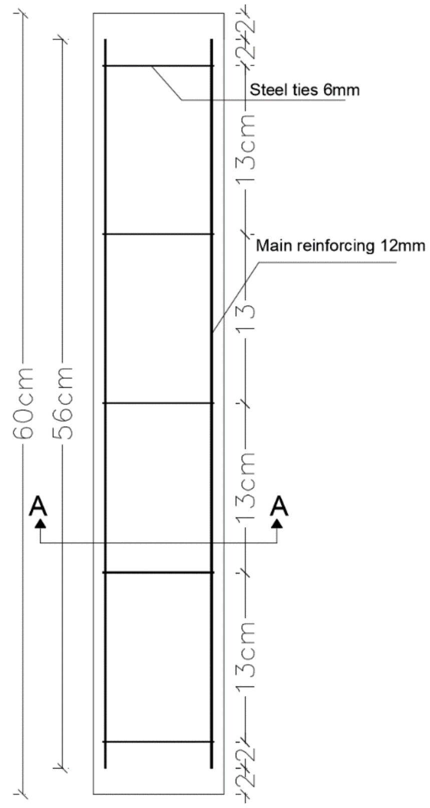
An experimental test conducted in a research intitled “Repairing and Strengthening of Damaged RC Columns Using Thin Concrete Jacketing”. This paper amid to investigate the efficiency of repairing damaged concrete columns using thin concrete jacketing (Arafa *et al.* 2019). The experimental program included casting of nine reference 300mm long reinforced concrete column specimens: three specimens had a cross-sectional dimension of 100mm×100 mm these cores were damaged by loading them with approximately 90% of their actual ultimate axial load capacities. then, the columns were repaired and strengthened by applying two jacketing materials, which were 25 and 35mm thick. the experimental program showed that an ultimate load capacity Pu = 331 kN, with axial displacement 0.65 at the ultimate load and 0.972 mm at failure.

Table 1 shows how the specimen was prepared in compliance with standards.

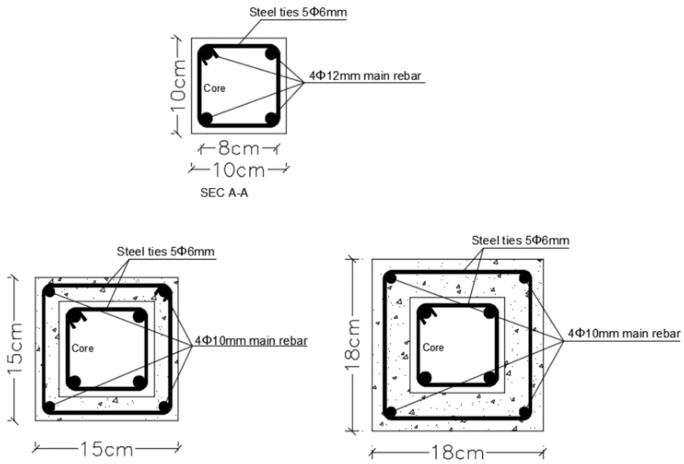
The longitudinal reinforcement ratios of all column specimens are at least 1%, various concrete mix types are generated based on the desired concrete compressive strength, as shown in Fig. 2.

3. Research methodology

The use of numerical modelling investigates the strengthening of the RC square column using SCC jacketing, based on experimental data acquired by the authors on SCC mixes produced from local raw materials. One column was loaded to failure as a control specimen, while the other columns



(a) Model Height



(b) Cross Sections

Fig. 2 Columns Modeling Specimens

were loaded to 0.60 of the ultimate loads as a service load to simulate the column in operation. Then, strengthen with the approaches listed in the methodical chart below Fig. 1. The investigation also included studying the effect of changing the column dimension, the impact of increasing jacketing thickness, and the concrete compressive strength of the SCC jacketing layer on the ultimate load-carrying capacity and axial displacement of uniaxially loaded square RC columns repaired and strengthened using two jacketing types using the verified numerical model parameters.

Table 1 shows how the specimen was prepared in compliance with standards.

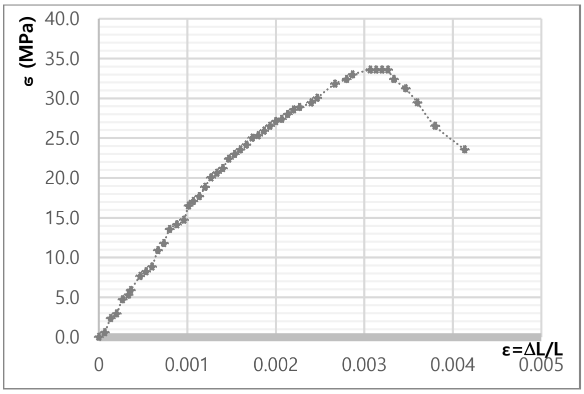
The longitudinal reinforcement ratios of all column specimens are at least 1%, various concrete mix types are generated based on the desired concrete compressive strength, as shown in Fig. 2.

4. Modelling of materials

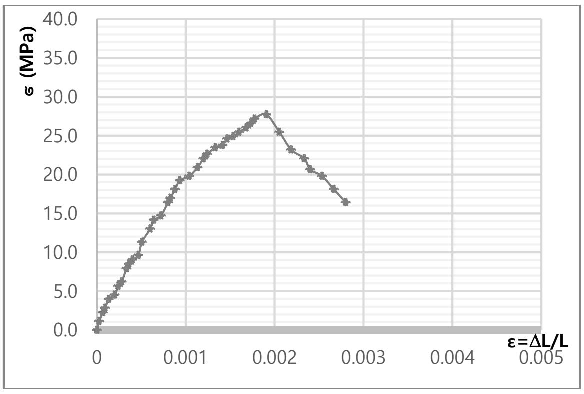
Concrete and steel reinforcement (rebar used as primary and transverse reinforcement) were among the materials used in column modelling (details of the materials used in the numerical work are shown in Tables 2 and 3.

Table 2 NSC and SCC mixing proportions

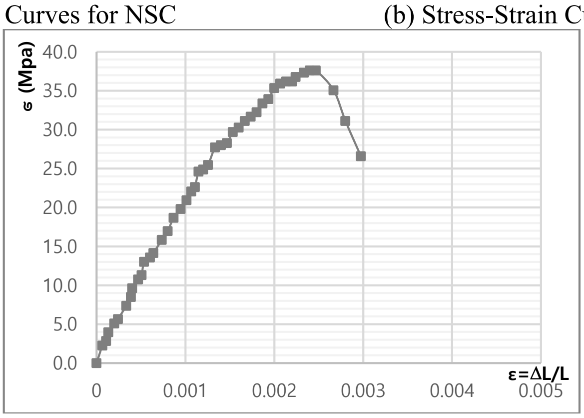
Mix	Material	Quantity (kg/m3)	Mix	Material	Quantity (kg/m3)
NSC	Coarse aggregate	881.4	SCC	Coarse aggregate	881.4
	Fine aggregate (sand)	592.8		Fine aggregate (sand)	592.8
	Cement	550		Cement	550
	W/C	0.45		W/C	0.39
	-			Superplasticizer	11



(a) Stress-Strain Curves for NSC



(b) Stress-Strain Curves for SCC-NN

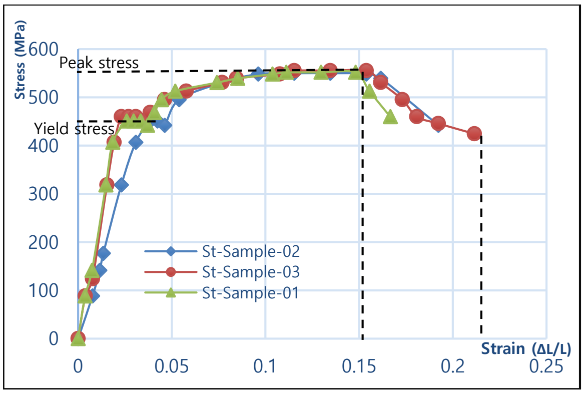


(c) Stress-Strain Curves for SCC-3500

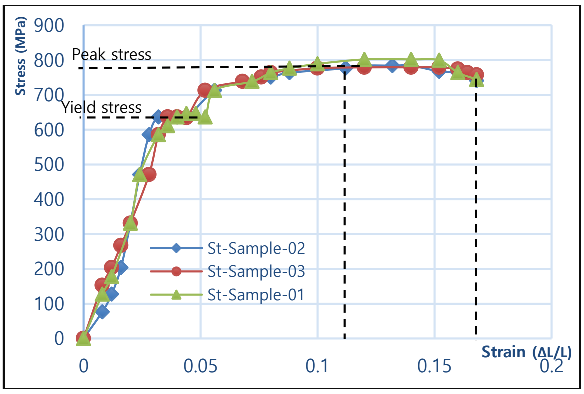
Fig. 3 Stress-Strain Curves for Concrete

4.1 Concrete

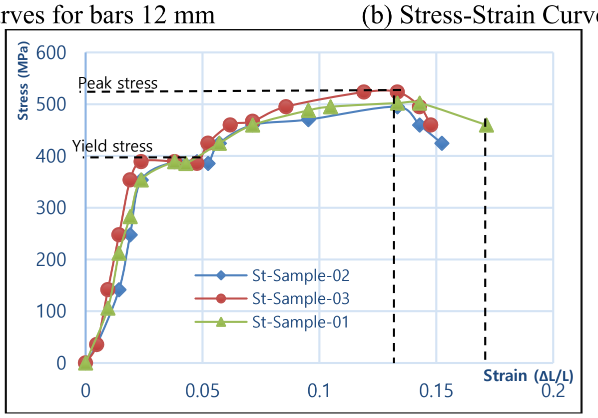
Each specimen has a square cross-section with dimensions of 100 mm on each side and 600 mm in height, as shown in Table 1. The concrete was handled as a solid element in order to produce an adequate stress distribution in a 3D analysis of finite elements. The compressive strengths of NSC and SCC are shown in Fig. 3 based on experimental results. This image depicts the general features of the used concrete.



(a) Stress-Strain Curves for bars 12 mm



(b) Stress-Strain Curves for bars 10 mm



(c) Stress-Strain Curves for bars 6 mm

Fig. 4 Stress-Strain Curves for Reinforcement bars

Table 3 Steel reinforcing bars proportions

Type#	Specimens	Diameter (mm)	Yield stress (MPa)	Peak stress (MPa)	Max strain (mm)	Number of samples
1	Longitudinal Steel Reinforcement bars	12	453	552	416	3
2	Longitudinal Steel Reinforcement bars	10	640	788	380	3
3	Transverse Steel Reinforcement bars	6	389	506	313	3

4.1.1 Normal Strength Concrete (NSC)

The NSC mix Table 2 is used to produce the unconfined (UC) columns "control column core" of the two groups 3500 and NN.

4.1.2 Self-Compacting Concrete (SCC)

Jackets are prepared by applying two jacketing kinds to the two groups of column cores, 3500 and NN. The SCC jacket contains the steel reinforcing cage. Table 2 shows the NSC and SCC mixing proportions.

Fig. 3 illustrates the Stress-Strain (σ-ε) diagrams of the NSC and SCC using the two types 3500 and NN (Tawashi and Alamoudi 2022a, 2022b).

4.2 Steel reinforcement

Two types of steel reinforcing bars are used to strengthen the UC columns and control column cores of the two groups, 3500 and NN. For longitudinal steel reinforcement, high-tensile-strength steel with a yield stress of 453 MPa is utilized, while steel reinforcement ties with a yield stress of 389 MPa are used. Three steel specimens with a diameter of 12mm and a length of 280 mm were tested, as were three steel specimens with a diameter of 10mm and a length of 260 mm (for SCC jacketing main reinforcing) and three steel specimens with a diameter of 6mm and a length of 230 mm. The primary longitudinal and transverse steel reinforcements' testing results are shown in Table 3.

The Stress-Strain (σ-ε) diagrams of the reinforcing steel bars also be illustrated in the Fig. 4.

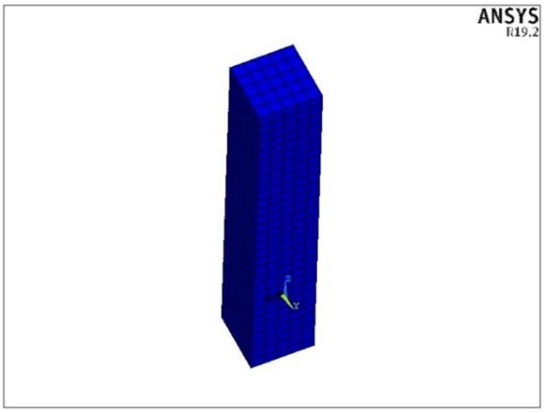
5. Finite elements analysis

The 3D finite element ANSYS software was used to analyses the test scenarios. Through the simulation of time-dependent behavior, contact algorithms, and material models with nonlinear characteristics, ANSYS can rapidly and correctly simulate engineering models. Additionally, ANSYS can depict aspects of engineering simulations like boundary conditions and a model's behavior under different standards. ANSYS is able to solve various matters using nonlinear problems. With this approach, the solution is divided into load stages, which are described in the software programme as load increments. Before proceeding to the next load increment, the model stiffness matrix is modified at the conclusion of each load increment to indicate changes in the overall structural stiffness. A suitable element was selected from the ANSYS software library to model each component of the column. For the concrete and jacketing, the Solid65 element was utilized. Each of its eight nodes has three degrees of freedom, which correspond to directions in the x, y, and z axes. This material is capable of withstanding three orthogonal axes of plastic deformation, crushing, and cracking. Element link 180 was used to simulate the stirrups and main longitudinal reinforcing bars. Each of the two nodes on Link 180 had three degrees of freedom.

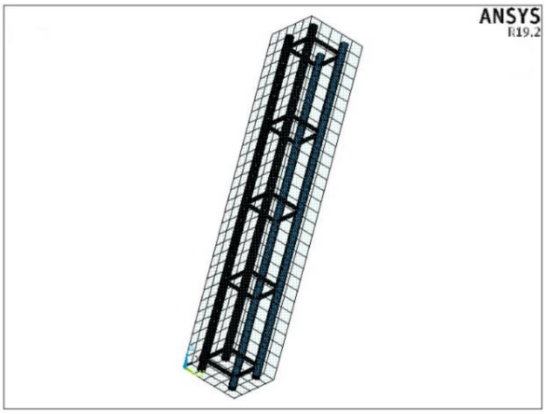
Concrete was used to build every specimen core (NSC), with a consistent compressive strength of 33.57 MPa. The jacketing for SCC-NN was 27.17 MPa, and for SCC-3500 it was 37.61 MPa; these are the real values gleaned from the experimental compression test. Four 12 mm-diameter bars served as longitudinal steel reinforcement in the core model, an d the stirrups were 6 mm-diameter. Four 10 mm-diameter bars served as longitudinal steel reinforcement in the jacketing. Other factors such as modulus of elasticity, poison ratio, de nsity, uniaxial cracking stress, and uniaxial crushing stress were also defined as following:

- Density = 25 N/mm3
- Modulus of elasticity = f/ε
- Poison ratio = 0.2
- Uniaxial cracking stress = 0.6√Fcu (MPa)
- Uniaxial crushing stress = Fcu (Mpa)

Reinforcing steel bars defined by yield stress, poison ratio, and modulus of elasticity. The mechanical characteristics of the longitudinal steel reinforcement and stirrups were taken according

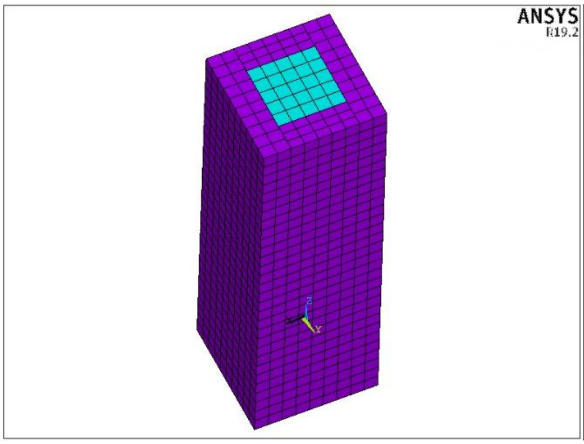


(a) Core mesh

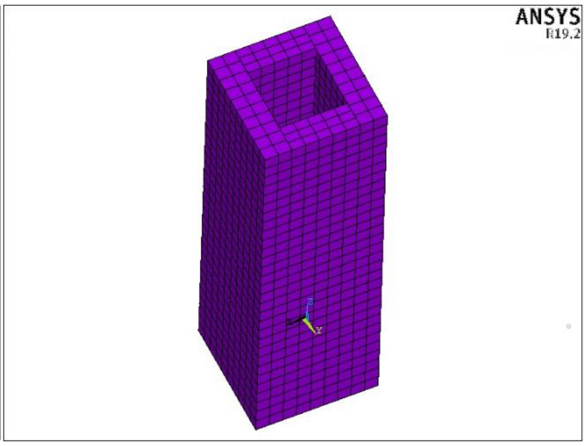


(b) Reinforcing steel bars

Fig. 5 The Control column 3D model



(a) Core and Jacket



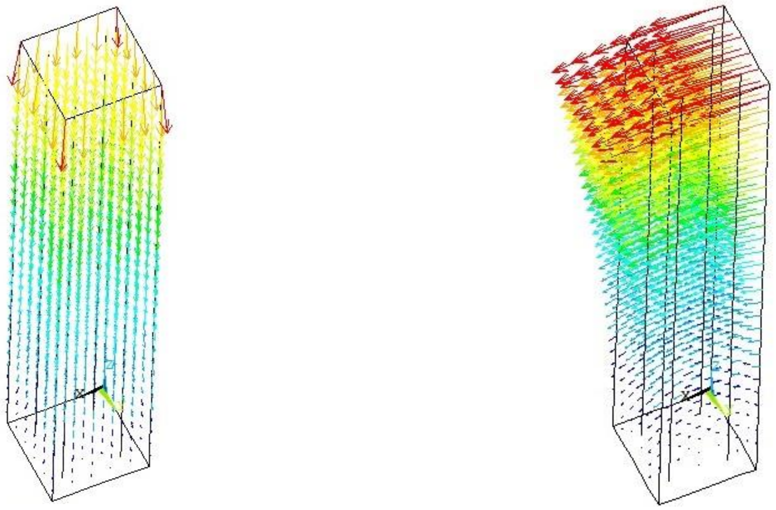
(b) Jacketing mesh

Fig. 6 Jacketing 3D Model

to Table 3 and the stress-strain values as shown in Fig. 5. Stirrups were spaced at 130 mm at the length of the column. The control column and the strengthened columns were modelled as shown in Fig. 6. All degrees of freedom were constrained at the base of the columns, and free at the top to simulate the actual boundary conditions in response to the earthquake.

Two types of forces were applied on the top nodes of the model. Vertical force represented regular load that affects the columns DL+LL. Horizontal force represents the earthquake load which happened at the specified moment. The maximum capacity of the short columns cross section is given as Eq. (1). The right side of the previous equation is multiplied by 0.3 taking into consideration the simple compression stress not more than $0.3f'_c$ during the service phase (Syrian Arab Code Committee, 2012).

$$N_u = 0.3 \times f'_c \left(A'_c + 1.17 \times \frac{f_y}{f'_c} \times A_s\right) \tag{1}$$



(a) Vertical compression (b) Vertical and Horizontal forces

Fig. 7 Column deflection direction

Table 4 Deflections in all directions

Specimens	Notation	Total cross section (mm)	Max DOF X (mm)	Max DOF Y (mm)	Max DOF Z (mm)
Control Column Core	UC	100 ×100	4.81	0.01	0.63
Specimens Jacketed from NSC mix	NSC	150 ×150	4.51	0.009	0.53
Specimens Jacketed from NSC mix	NSC	180 ×180	4.72	0.01	0.57
Specimens Jacketed from SCC mix	3500	150 ×150	2.91	0.06	0.52
Specimens Jacketed from SCC mix	3500	180 ×180	3.05	0.08	0.58
Specimens Jacketed from SCC mix	NN	150 ×150	3.06	0.08	0.55
Specimens Jacketed from SCC mix	NN	180 ×180	3.49	0.11	0.70

6. The research findings and discussion

Measuring the change in structural behavior of columns under normal vertical and horizontal seismic stress is critical for both overall structural evaluation and selecting the most efficient and cost-effective structural strengthening technique. It is critical to determine the deflection values in all directions, external force pressures, and cracks along the column.

The radial instantaneous deflection of the column can be illustrated by the action of the vertical and horizontal forces, as shown in Fig. 7. It was found that the momentary seismic horizontal forces had a significant impact on the column's deflection behavior by increasing a seven-fold in the

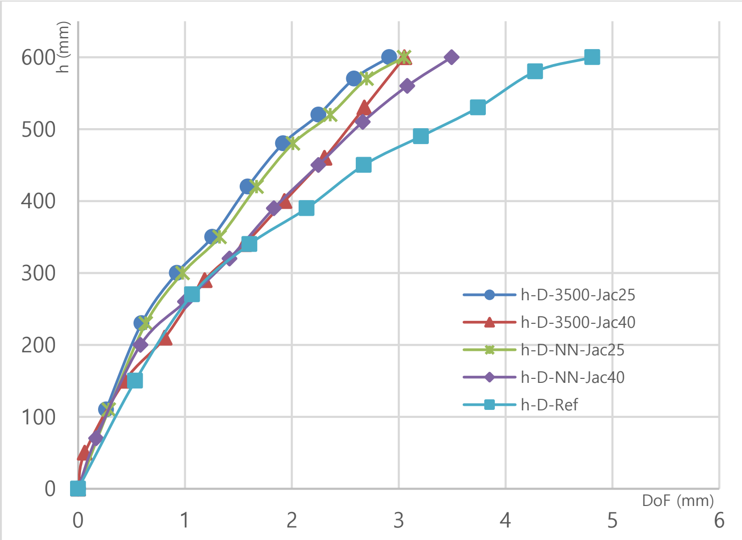


Fig. 8 Hight -Deflection (h-D) Curves

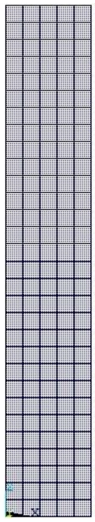
Table 5 Stress in Specimens (-comp/+tens)

Specimens	Notation	Total cross section (mm)	Max Stress X (MPa)	Max Stress Y (MPa)	Max Stress Z (MPa)
Control Column Core	UC	100 ×100	-3.89/+2.86	-5.04/+1.74	-24.15/+2.19
Specimens Jacketed from NSC mix	NSC	150 ×150	-4.10/+2.50	-5.33/+1.81	-26.12/+1.92
Specimens Jacketed from NSC mix	NSC	180 ×180	-4.18/+2.11	-5.24/+2.02	-36.37/+2.42
Specimens Jacketed from SCC mix	3500	150 ×150	-5.63/+3.19	-10.04/+3.35	-31.32/+1.89
Specimens Jacketed from SCC mix	3500	180 ×180	-5.70/+2.28	-10.10/+2.55	-32.16/+3.46
Specimens Jacketed from SCC mix	NN	150 ×150	-5.18/+2.79	-9.62/+2.52	-30.75/+1.53
Specimens Jacketed from SCC mix	NN	180 ×180	-9.15/+3.01	-7.84/+2.04	-26.85/+2.52

horizontal deflection in the direction of the force apply and a six-fold increase in the vertical deflection.

Three levels were evaluated: the deflection at the height of the column Table 4, the generated stresses Table 5, as well as the distribution and propagation of cracks. As demonstrated, the method of strengthening by utilizing SCC concrete jacketing improved the deflection behavior in the direction of the seismic force. The values of the maximum deflection generated were taken for each study case.

The deflection along the column under simple compression and seismic force can also be illustrated according to the following curves in Fig. 8. Additionally, the column's deflection behavior


(a) Vertical compression

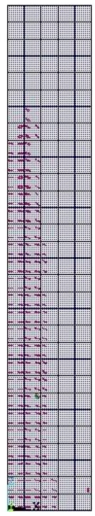
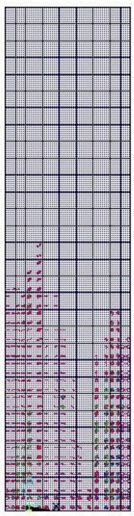

(b) Vertical and Horizontal forces

Fig. 9 Distribution of cracks in reference core


(a) SCC-3500

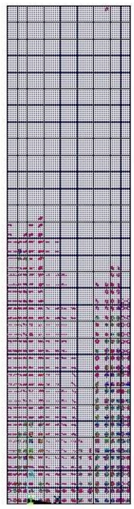
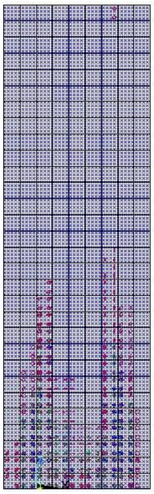

(b) SCC-NN

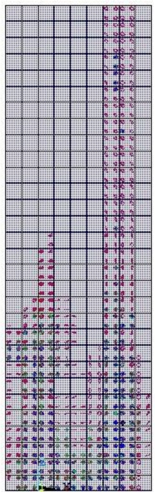
Fig. 10 Distribution of cracks with jacketing thickness 25 mm

has improved when compared to the reference sample, increasing from 27.4% to up to 39.5% when using a 40 mm thick SCC-NN jacket and an average of up to 36.6% when using a 25 mm thick SCC-3500 jacket. The shift is visible starting at the bottom of the lower third of the column, and it is correlated with the jacketing's thickness, material type, and mechanical properties.

The analysis also revealed an intriguing distribution of cracks along the column, particularly when horizontal forces were applied. Cracks had no discernible impact when there was only simple



(a) SCC-3500



(b) SCC-NN

Fig. 11 Distribution of cracks with jacketing thickness 40mm

compression. However, cracks started to appear and spread as a result of the horizontal force, which stood in for the instantaneous seismic load. Fig. 9 In the case of the reference sample, the column's portion developed cracks that failed the tensile test. The shape of the distribution and spread of cracks were altered in the case of the column with a casing of the type SCC-3500 and a thickness of 25 mm. Fig. 10 findings revealed that cracks formed thickly in the lower part of the column in both compressed and tightened sections alike. The formation and distribution of cracks in the column with a 25 mm thick SCC-NN casing were similar to the previous case, with the exception that they were more pronounced when the compressed and tensile fibers.

The results showed a distribution that was similar to the previous case and the distribution of cracks in the tensile and compressed zones but with a light thickness and a lower height of spreading in the case of the column with a casing of the type SCC-3500 and a thickness of 40 mm. Fig. 11 A contentious distribution in the case of the column with the SCC-NN type of casing and a thickness of 40 mm, as the cracks spread more intensely than in the previous case in the tensile and compression zones, particularly in the compression region, where the cracks spread to the end of the column, particularly at the contact area between the casing and the core, and the element failed on compression.

According to study cases, the demonstrated the significance of using sufficient compression strength of the jacketing material, not less than the strength of the reference column to prevent the failure at the compression zone, the failure of the strengthening, and the occurrence of a defect in the structural system.

8. Conclusions

The purpose of this work was to identify changes in the structural assessment criteria on concrete columns strengthened by self-compacting concrete SCC jacketing while understanding the structural behavior through numerical analysis. And the key findings are as follows:

- Strengthening of columns using concrete jacketing had a favorable effect on the element's behavior when subjected to an instantaneous force simulating the earthquake.
- The structural behavior of the columns has improved by decreasing the deflection of the columns up to 36.6% in the case of a 25 mm thick using SCC-3500 jacketing.
- The investigation indicated a distribution of cracks in the tensile and compressive zones and predicted the occurrence of a fragile and sudden failure of the column in the compressive zone, which is undesirable.

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Author contributions

1*a,1a Made the methodology and substantial contribution to the design of the article. The acquisition, analysis, interpretation, and investigation of data. Managed and funded the work. Originally drafted the article, revised it, and edited it critically for important intellectual content.

1a,2b: Conceived and designed the analysis. Support in the contributed data and analysis tools. Approved the version to be published.

Competing interests

Authors declare that they have no competing interests.

Data and materials availability

All data are available in the main text or the supplementary materials.

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