International Journal of Civil Engineering
ISSN: 2348-8352 / https://doi.org/10.14445/23488352/IJCE-V10I6P108

Volume 10 Issue 6, 74-85, June 2023

Original Article

Strengthening of RC Beams using SWM SCC Jacketing, A FE Numerical Modelling Study

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Received: 30 March 2023 Revised: 26 May 2023 Accepted: 13 June 2023 Published: 30 June 2023

Abstract - *Strengthening of reinforced concrete (RC) beams with Self-compacting concrete (SCC) jacketing reinforced with galvanized welded steel wire mesh (SWM) has been an important area of study so far. Increasing the mechanical characteristics of (RC) beams and structures to maintain the required service life and load capacity of any (RC) structure is an exciting study area. In this research, a Finite Element (FE) investigation is conducted on a series of (RC) beams that were previously strengthened experimentally with Self-compacting concrete (SCC) jacketing reinforced with galvanized welded steel wire mesh (SWM). A (FE) model will be conducted to predict the strengthened beams' load-deflection behaviour and crack/failure pattern. Based on both experimental and numerical model achieved results, the FE model results will give some important conclusions and recommendations regarding the experimental strengthening of RC beams using this technique. Another external steel plate strengthening technique will be used and checked to compare with the SCC SWM strengthening technique. The FE results showed that the strengthened jacketed samples (with SWM SCC in addition to an external steel plate) restored, on average, 150 % and 172 % of the original control beams' load capacity for groups A and B, respectively. Using an external steel plate slightly increases the stiffness and decreases the ductility of the tested beams. Even though it increased the ultimate load capacity of the strengthened beams with SCC.*

Keywords - *Strengthening RC beams, SCC jacketing, FEM, CDP, Steel plate.*

1. Introduction

Palestine is a coastal country with more than 270 Km of coastline length on the Mediterranean Sea. This geographic location with the associated environmental conditions may have a considerable effect on the deterioration of existing concrete structures built in Palestine; from the literature, it was found that the following causes are behind the majority of the structural defects in the Palestinian RC buildings:

1. Many of the exposed concrete facades of RC buildings along Palestine's seashore show the typical cracking and spalling caused by corrosion of reinforcing steel near the concrete surface, even after a few years of service. Field observations and tests confirm that high chloride concentrations near the reinforcing steel near the concrete surface cause premature corrosion onset (Chanoch Jaegermann, 1990).
2. Vertical Flexural cracks due to excess loadings, a previous study by (Nicolae Gluck et al., 2015) studied the existing structures in Palestine and provided an assessment of the structural ability to stand the increased loads of the actual demand; the study found that the temperature changes can lead to crack development, FRP sheets as well as steel profiles can be used to strengthen the RC walls studied.
3. Diagonal Shear cracks due to inappropriate sections.
4. Fire and any other accidental damages to the structures.

Many different strengthening techniques are available for reinforced concrete (RC) structures. The strengthening or repair technique is necessary for RC structures during their service life if they do not meet the code of practice requirements due to different types of deterioration and damage. Many Palestinian RC structures constructed in the past using the older design codes are structurally unsafe according to the new design codes and hence need strengthening.

2. Literature Review

The technique of bonding steel plates to the concrete surface has been used on several structures worldwide to enhance load-carrying capacity (Rodríguez et al., 2009). Other available strengthening techniques are being used, such as the addition of carbon-reinforced polymer CFRP rods or Sheets (Composite Section) can also be a promising solution to enhance the load-bearing capacity of RC beams using different techniques (such as near surface mounted NSM or externally bonded laminate EBR), the CFRP can increase the stiffness and ultimate bearing capacity of corroded RC beams repaired with CFRP NSM rods. (Belal Belal Almassri et al., 2014, 2020), another common strengthening technique is RC jacketing, where RC jackets can be applied by adding new concrete to three or four sides of the beam (Andreas J. Kappos et al., 2002). (Y. G. Diab, 1998) carried out an experimental program to evaluate the effectiveness of repairing RC beams with a layer of sprayed concrete.

The experimental results (R. Tuğrul ERDEM et al., 2022) indicate that jacketing using sprayed concrete to strengthen RC beams can effectively increase their load carrying capacity or stiffness, and the strengthened beams showed high ductility before failure.

Reinforced concrete (RC) jacketing has become a widespread structural technique(Arimanwa and Sule, 2019) in various civil engineering applications such as retrofitting, rehabilitation and strengthening and even in repairing several structural elements. The usage of jacketing in primary structural members having self-compacting concrete (SCC) reinforced with steel wire mesh (SWM) is gaining wide acceptance because of its significant effect on both ductility and the ultimate carrying capacity. Members constructed from SCC/SWM jacketing also exhibited a noticeable enhancement in the energy absorption capacity, cracking resistance and stiffness (Mohamed A. Abu Maraq et al., 2021; Bassam A. Tayeh et al., 2020).

(Mohamed A. Abu Maraq et al., 2021) some experimental tests have been conducted up to failure; eleven strengthened samples, four monolithically poured, and three original control beams. The eleven specimens are strengthened using the U-Jacketing technique, in which a relatively thin reinforced SCC layer is applied for the bottom width and both vertical sides of the original beams.

The strengthened beams are categorized into groups A and B based on test variables: the SWM properties and the bonding mechanism. This research also clarifies the flexural capacity, ductility, stiffness, crack width and deflection. Based on the achieved test results, all strengthened beams were designed to fail flexibly.

The first group of strengthened beams restored 110% of the original control beams' load capacity on average, whereas the second strengthened group resorted to 163% on average. Moreover, it was found that the strengthened beams acted in the same manner as the monolithic control beams and acted as a single unit. Accordingly, it is concluded that this strengthening technique can be used confidently in real-life applications, especially for low-priced constructions.

However, the studies on verifying this strengthening technique numerically are still quite limited. SWM is frequently used in various structural applications: shell structures, precast elements, bridge deck slabs, concrete road pavement, underground tunnels, water tanks, concrete sewer pipes, culverts, chimneys and even masonry walls. SCC is one of the innovative types of concrete that have gained considerable attention in the recent decade and is proper for the production of reinforced concrete which can flow under its own weight (Adeyemi Adesina, 2020; Ghasan Fahim Huseien, and Kwok Wei Shah, 2020; Hossein Sasanipour, and Farhad Aslani, 2020).

SCC provides an opportunity to produce reinforced concrete by eliminating the need for excessive vibration, particularly in highly congested reinforcement within concrete structures in a less energy-intensive manner. Also, SCC has been shown to exhibit lower permeability due to its composition, which is mainly made up of fine particles resulting in a more densified microstructure (Wu-Jian Long et al., 2016; Hossein Sasanipour, and Farhad Aslani, 2020; Anil Kumar et al., 2023). Thus, more resistance to severe environmental exposure. The following points can be concluded from the literature:

- FEM study needs to be validated to study some beams repaired with SCC SWM Layers.
- There is a lack of literature on the parametric study of the RC beams strengthened with SCC SWM.
- The literature did not employ this repair technique for old and deteriorated RC beams.
- No previous research article proposed a hybrid strengthening technique using the SCC jacketing and other techniques, such as the external steel plate.

The present study follows up on the work conducted by (Mohamed A. Abu Maraq et al., 2021), a well-known FE commercial software ABAQUS is adopted to conduct numerical analysis. The validity of FE numerical analysis will be illustrated in anticipating the flexural performance of RC beams with SCC jacketing reinforced (Dharmesh, and Govindaraju, 2023) with SWM layers. Numerically obtained results will be validated to those experimental counterparts regarding crack patterns and the load-carrying capacity versus the mid-span deflection.

The validated FE model was then widened to analyze the influence of adding external steel plates to the lower surface of the jacketed specimens on both the ultimate capacity and stiffness. The significance of the study arises from the fact that if an approach of FE can be validated, designers can predict the structural performance of various hybrid strengthening techniques on RC/SWM/SCC beams without the need for lengthy and expensive experimental testing programs.

3. Experimental Context

3.1. Test Program Description

The geometric characteristics for all initial core beams (i.e. before jacketing process) are similar. The total beam length is 1200 mm, with a width to depth of 100 mm x 150 mm and a shear span of 450 mm, as illustrated in Figure 1. The RC beams are designed according to the ACI-318 code; the top longitudinal steel reinforcement is 2Ø6 mm, while the bottom longitudinal steel reinforcement is 2Ø10 mm, and the shear reinforcement is also provided using a 6 mm diameter mild steel bar at an equal spacing of 50 mm.

The test program includes eighteen relatively small RC beams tested experimentally to study the flexural capacity under a 4-point bending load test configuration until failure with a 1050 mm clear span. Three beams, denoted as C, are used as reference control beams with a typical cross-section, as seen in Figure 1, with a width to depth of 100 mm x 150 mm. Four beams, denoted as M, are used as reference control beams when compared with their SCC jacketed counterparts' specimens and are cast monolithically with the similar reinforcement cage of type C beams as well as SWM reinforcement, as seen in Figure 2, with a width to depth ratio of 160 mm x 200mm. The last eleven beams are broken into groups, denoted GA and GB, and used as strengthened samples.

The typical initial beams are strengthened externally by applying a U-wrapping jacket for three beam surfaces: the two beam sides and the lower beam soffit. The strengthened specimens have a cross-section of 160 × 200 mm with a total length of 1200 mm. The adequate depth of Group A and Group B samples equals 183.25 mm and 182.25 mm, respectively, as shown in Figures 2 and 3.

The jacket reinforcement of the strengthened specimen of Group A is Ø3.5 mm of 25 mm square opening galvanized SWM. In contrast, Group B has Ø5.5 mm of 50 mm square opening galvanized SWM with three different bonding mechanisms. The three bonding techniques applied in both groups to prevent or delay the inter-laminar shear at the interfaces surfaces are Ø 8mm expansion bolts, I-shape Ø8 mm diameter steel dowels and surface roughening. The cross-sectional geometric characteristics of both groups (i.e. after the jacketing process) are shown in Figure 3 and Figure 4.

3.2. Materials Mechanical Properties

The mechanical properties of the ordinary concrete and the SCC, precisely the compressive strength and the tensile strength are determined experimentally using three cubes and three cylinders for each test. The following tables summarize the proportions of the materials job mix design used in producing the ordinary concrete and the SCC.

3.2.1. For Ordinary Concrete (Used in Core Beams)

Table 1. Ordinary concrete proportions (kg/m^3)

Material	Proportion (kg/m^3)
Cement (CEM II/AM-SVL 42.5N)	350
Water	175
Coarse Aggregate (0.15-19 mm)	1197.90
Fine Aggregate (dune sand)	616.60
W/C ratio: 0.50, Slump: 25-100 mm	

3.2.2. For SCC (Used in the Jacketing Process)

Table 2. SCC proportions (kg/m3) according to EFNARC recommendations

Cement (CEM II/AM-SVL 42.5N)	Limestone Powder (< 0.075 mm)	Free water	Superplasticizer - Sika Viscocrete 5920	Coarse Basalt Aggregate (2-9 mm)	Fine Aggregate (dune sand)
522.5	27.50	141.47	13.75	868.85	894.26
(Water/Powder) by volume = 0.89, Powder content = (Cement +Limestone Powder) Slump flow test (mm) =765.00 T500 slump flow (Sec.) = 2.95 L-box = 1.00 V-funnel (Sec.) = 5.00					

3.2.3. For Steel Reinforcement (Used in Core Beams)

Table 3. Steel reinforcement test results

Diameter (mm)	Average yield Stress, fy (MPa)	Average ultimate Stress, fu (MPa)	(%) Elongation
10	444.70	689.90	18.33
6	412.23	749.51	18.00

3.2.4. For SWM

Table 4. SWM test results (used in the jacketing process)

Diameter (mm)	Average yield Stress, fyw (MPa)	Average ultimate Stress, fuw (MPa)	(%) Elongation
5.50	300.58	418.60	6.42
3.50	250.74	280.55	8.20

3.2.5. For Shear Connectors

The two types of shear connectors used in the experimental investigation are deformed steel bars of Ø8 mm diameter and the expansion bolts of Hilti type (HSA M8 35/25/-) with mechanical properties mentioned in Maraq et al., 2021. Figure 5 shows the dowels installation.

3.3. Strengthening Technique

In the first stage, the initial core specimens should be produced by using the wooden moulds that were painted with the form release agent properly to ease removing the samples. Then, the steel cages were inserted within these moulds; the ordinary concrete was poured according to design proportions. All beams were stored under ambient conditions at nearly 25°C in the lab after they had been removed from their moulds. Quality control cylinders and cubes were taken during each casting day and kept under the same ambient condition. Potable water was used to cure the beam specimens for 14 days after removing the moulds. In the second stage, the three control beams were loaded up to failure, and the analysis of the specimens' response was recorded to emulate the service load in practice. The remaining samples were primarily loaded to about 30 per cent capacity of the control beam. Then, the wooden moulds were prepared after being painted with a proper release agent to produce the enlarged beams (i.e. jacketed specimens). Both the SWM's cage and the initial core beams were inserted within these moulds carefully to ensure the required concrete cover in the up-side-down shape to ease the pouring process of the SCC, as shown in Figure 6. After that, the SCC was poured according to the design proportions in Table 2, as shown in Figure 7. Quality control cylinders and cubes were also taken during each casting day, and potable water was used to cure the enlarged beam specimens for 14 days after removing the moulds.

Finally, all beams were loaded with two symmetric concentrated loads and edge-supported on two simple rollers on the hydraulic loading machine with a capacity of 200 kN. Then, the loads were gradually applied to the beams in leaps of 2.35 kN until failure. All instruments are precisely prepared to monitor the responses of test specimens throughout the investigation. The load and its corresponding mid-span deflection, first crack load, failure pattern and ultimate load are also conducted for each beam after they had initially bleached to observe the crack propagation during the testing. The following Figure 8 shows the loading test setup while more experimental data and results are found elsewhere (Mohamed A. Abu Maraq et al., 2021).

4. FE Numerical Modelling

In the present study, the nonlinear finite element (FE) is used through ABAQUS to build a 3-D model for the control RC beam (CB), which was previously tested experimentally, strengthened beams from both groups A and B were also simulated (GA, B and GB, B), one more beam was proposed numerically by using an external steel plate, (GA, BS and GB, BS). This innovative hybrid repair system is proposed to increase the flexural capacity of the strengthened beams to reach the maximum efficiency of this strengthening technique. The verification of the FE model is first implemented on the beams which were tested experimentally; then, the external steel plate is added to the FE model in order to simulate the global behaviour of strengthened beams; different reinforcement ratios of the SWM were used in order to study the relationship between ductility and stiffness in each strengthening technique.

4.1. Overview of the FE Model

In this model, the ordinary concrete and SCC were simulated as deformable solid elements, both types of concrete were defined using the concrete damaged plasticity model CDP, and the steel bars, steel connectors, SWM and the external steel plate were simulated using a deformable beam element. In contrast, steel stirrups are modelled using truss elements. The chemical adhesive is neglected in this model because the previous study of José M. Sena Cruz et al. (2006) showed that the influence of the epoxy adhesion on the global behaviour and the crack pattern is meagre and can be neglected.

4.2. Concrete Properties

Mainly, there are two material modelling approaches for concrete in ABAQUS: the concrete smeared cracking and the concrete damaged plasticity model (CDP). Interchangeable use of both models is valid in the case of plain concrete and reinforced concrete. The present study adopts the concrete damage plasticity model for modelling ordinary and SCC concrete. The mechanical properties of concrete are shown in Table 5.

Table 5. Properties of hardened concrete specimens used in the FE model

Item	Fc'(MPa)	ft (MPa)	Ec(MPa)	υ
Value	40	3.5	34000	0.2

Modelling concrete requires considering a set of parameters according to the CDP model to capture concrete behaviour accurately. These parameters are summarized in

Table 6. Many researchers used these parameters and the results they obtained agreed with the experimental tests for different structural elements from previous research. The compression damage parameter (dc) in the CDP model represents the decay in the elastic stiffness due to compressing the concrete. In contrast, the tension damage parameter (dt) represents the decay in the elastic stiffness due to tensioning the concrete. Both parameters are calculated following the method proposed by Mahdy et al. (2004).

Table 6. Parameters of the concrete-damage-plasticity model

Parameter	Value
Dilation angle (ψ)	36°
Eccentricity (e)	0.1
f_{b0}/f_{c0} (ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress	1.16
K (the ratio of the second stress invariant on the tensile meridian)	0.667
μ (viscosity parameter)	0.0005

The concrete used to build the current FE models is given a compressive strength of 40 MPa and an elasticity modulus of 34000 MPa.

However, Figure. 9 presents the data needed to define the ABAQUS concrete material. Figure. 9(a) shows a curve of uniaxial compression stress versus inelastic strain of concrete, while Figure. 9(b) shows a curve of tension stress versus cracking strain of concrete. The curve in Figure. 9(c) displays the relationship between the compression damage parameter and the inelastic strains, while Figure. 9(d) shows the change in the tension damage parameter at various cracking strains.

4.3. Steel Properties

The behaviour of the steel reinforcing bars and steel stirrups is assumed elasto-plastic. Table 7 shows the average values adopted in the steel reinforcement and wires numerical model. The detailed specimen testing procedure is described in the published experimental study paper.

Table 7. Steel properties adopted in the FE model

Specimen Type	Young's modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)
Steel bar (10mm)	200	444	690
Steel bar (6mm)	200	412	750
Steel Wires (5.5mm)	200	300	419
Steel Wires (3.5mm)	200	250	280

4.4. External Steel Plate Properties

Ibrahim M. Metwally (2014) implemented a FE model using ABAQUS to investigate the strengthening technique's behaviour using epoxy-bonded steel plates. The study found that increasing the steel plate thickness increases the stiffness of the RC element. In order to have a failure load less than the shear design capacity, a steel plate thickness of 1.5 mm and width of 80 mm are assumed for both proposed beams, GABS and GBBS.

The proposed beam section, which is strengthened using both (SWM SCC and External steel plate) is shown in Figure. 10, complete contact was assumed between old and new concrete surfaces since no debonding was noticed in the experimental results; moreover, the staggered expansion anchors used experimentally made the contact assumption between the two surfaces acceptable. Five beams were modelled using the commercial software ABAQUS, including different strengthening techniques; the properties description of all beams studied are shown below in Table 8.

Table 8. Properties of all beams (experimental and FEM)

Beam	Cross Section	SWM Properties		External Steel Plate	Strengthening Technique
	(b × h) (mm)	Diameter (mm)	Open (mm)	(b × h) (mm)	
CB1	100 × 150	-	-	-	-
GAB1	160 × 200	3.5	25 × 25	-	SCC + SWM
GBB1	160 × 200	5.5	50 × 50	-	SCC + SWM
GABS	160 × 200	3.5	25 × 25	80 × 1.5	SCC + SWM + External Steel Plate
GBBS	160 × 200	5.5	50 × 50	80 × 1.5	SCC + SWM + External Steel Plate

5. Results and Discussion

5.1. Load Deflection Curves

The FE model predicts the global behaviour of the beams (GAB1, GBB1, and control beam CB1) studied experimentally. The FE load-deflection curves recorded from the FE model using ABAQUS agree with the experimental results. This is from the load-deflection curves for all beams presented in Figure 11. The behaviour of newly proposed models GABS and GBBS are also presented along with the behaviour of other beams to observe the change in the behaviour and the load capacity. This innovative hybrid strengthening technique uses an external steel plate in addition to SWM.

The ultimate load capacity for the new proposed beam GABS from group A (SWM diameter of 3.5 mm was used) in addition to the external steel plate was 113 kN; the load capacity increased by 33 kN compared to GAB1; on the other hand, if it is reinforced with 5.5 mm (Group B) in addition to an external steel plate, the ultimate load capacity was 119 kN which was increased by 19 kN compared to GBB1. Using this innovative strengthening technique (SWM and external steel plate), the first beam GABS restored an average of 150% of the original control beam load capacity. In contrast, on average, the second proposed beam GBBS resorted 172% of the original control beam load capacity.

5.2. Ductility and Stiffness

The proposed models' GABS and GBBS (strengthened with SMW and external steel plates) are noticed to have less ductility index ($\varepsilon_u/\varepsilon_y$) than the beams which were repaired using SWM only (GAB1 and GBB1). A ductility index of 1.2 was calculated for both beams GABS and GBBS. In contrast, the experimental and FE ductility index values for GAB1 were 1.8 and 1.6, respectively, while the experimental and FE ductility index values for GBB1 were found to be 1.9 and 1.5, respectively. On the other hand, the stiffness of the newly proposed models GABS and GBBS increased, as observed in the linear stage. The same result was found by Belal Almassri et al. (2020), as the external steel plate was used to repair the corroded RC beam, which was repaired with an NSM CFRP rod in bending. Figure 12 shows the ductility index values for all beams, and Figure 13 presents the stiffness ratio (slope after strengthening / slope before strengthening) for both strengthening techniques (SWM and external steel plate).

5.3. Modes of Failure

The failure cracking patterns of the strengthened beams with SWM were only tested experimentally (Figure 14 (a)), taken from the visual observations during the experimental tests. This Figure shows a typical failure mode, noted for almost all tested specimens; all specimens presented flexural cracks extending from the specimen's lower surface to the centre of the bearing plate. Furthermore, flexural cracks located at the mid-span where the maximum flexural moment occurred indicate jacketed samples using SWM exhibited ductile mode of failure and pure flexural cracks pattern. Figure. 14 (b) shows how the FE model predicted the failure mode, which was recorded experimentally. Furthermore, in the proposed models' GABS and GBBS, which were strengthened using an external steel plate in addition to SWM SCC, the mode of failure changed from flexural cracks at the middle to significant diagonal shear crack failure, as shown in Figure 15.

5.4. Effect of Steel Plate Thickness and Width

A numerical analysis was carried out on the GABS beam, which was theoretically strengthened using both SCC and external steel plate with increasing the thickness of the strengthening plate to 3,5 and 7 mm. The results are shown in Figure 16. It can be seen that prior to the yielding point, increasing of thickness of plates does not influence the load-deflection characteristics.

However, after yielding, the load-deflection curve becomes relatively stiffer, especially for beams strengthened with external steel plates with 3, 5, and 7 mm thickness. The load-deflection curves also show that deflections generally decrease with the thickness of the steel plate for a given load. Also, increasing the plate thickness caused remarkable growth in the capacity of beams till thickness equalled 5mm; beyond this limit, the load decreased (at t = 7 mm), as shown in Figure 16. This refers to the higher stiffness of strengthened beams, making it easy to fail by crushing the concrete in the compression area. Figure 17 shows the ultimate load capacity for different steel plate thickness values. The optimum load capacity was found when the thickness was 5 mm. At the same time, less than 1.5 mm gave much lower load capacity values than the range between 3-7 mm; after 7 mm, the ultimate load capacity was dropped due to increased stiffness in RC beams.

Figure 18 presents the results of the ultimate load capacity values of the GABS beam using six proposed steel plate width values (40,60,80,100,130 and 160mm); the plate length (1200 mm) and thickness (1.5 mm) were fixed here at this point. Figure 34 shows that the variation of the width has not nearly any effect on the ultimate load capacity and stiffness (Figure 19) (which ranges from 100 to 113 kN for ultimate load capacity). Figure 19 shows an identical stiffness value for different plate width values; even for steel plate width less than 60 mm, the load capacity values did not give as many values as for 80-160 mm.

5.5. Effect of Concrete Compressive Strength Fc.'

Three compressive strength values were used (21 MPa, 32 MPa and the one which was already used and fixed in all previous sections, 40 MPa); the change in Fc' will be applied to the GABS beam, the concrete compressive strength factor will be studied along with the external steel plate, the steel plate is fixed to be 80 mm width and 1.5 mm thick. Figure 20 presents the load-displacement curves for various proposed concrete compressive strength values; using Fc'=40 MPa will give the optimum load capacity value for repaired beam, while for Fc'=32 MPa, there was only an 8 kN difference compared to 40 MPa concrete, the stiffness of 40 MPa reached its highest value.

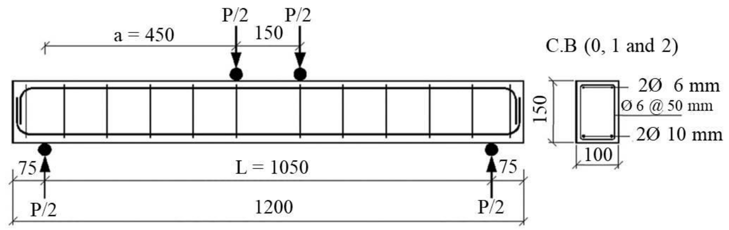

Fig. 1 Typical beam geometry and cross-section detailing in mm (Maraq et al., 2021)

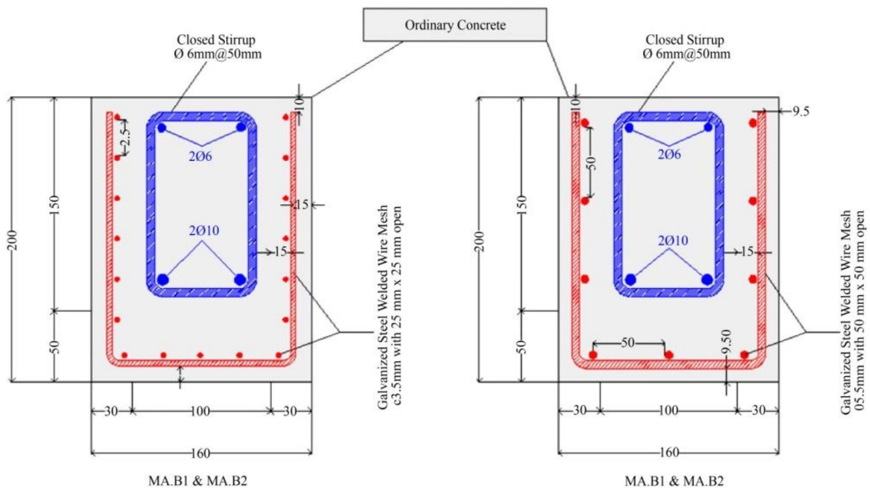

Fig. 2 Monolithic beams cross section (mm) (Maraq et al., 2021)

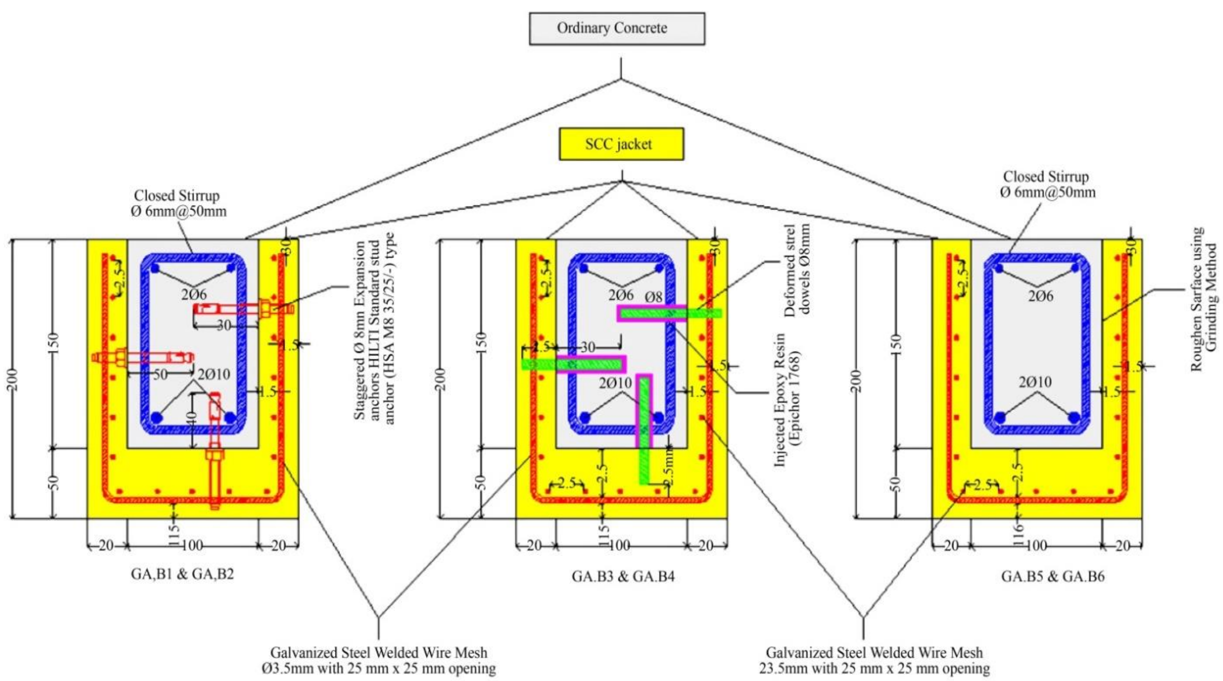

Fig. 3 (Group A) strengthened beams (dimensions in mm) (Maraq et al., 2021)

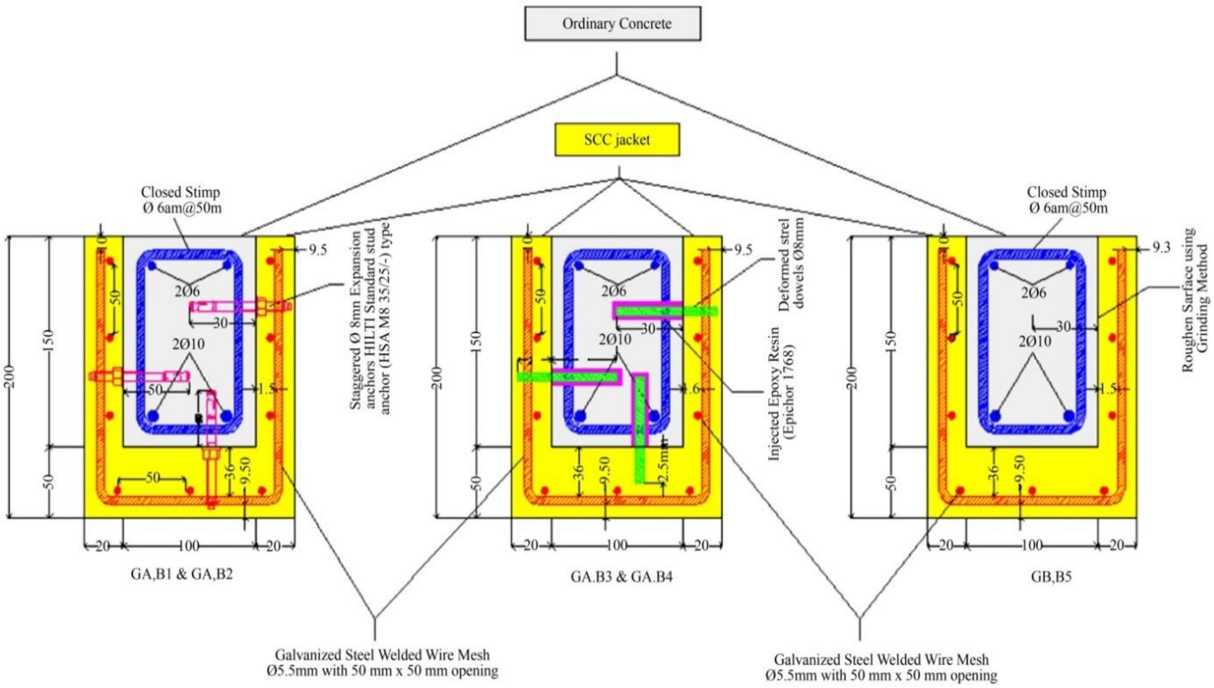

Fig. 4 (Group B) strengthened beams (dimensions in mm) (Maraq et al., 2021)

Fig. 5 ∅ 8mm dowels installation (Maraq et al., 2021)

Fig. 7 Pouring SCC concrete

Fig. 6 Preparation of the moulds

Fig. 8 Test set-up

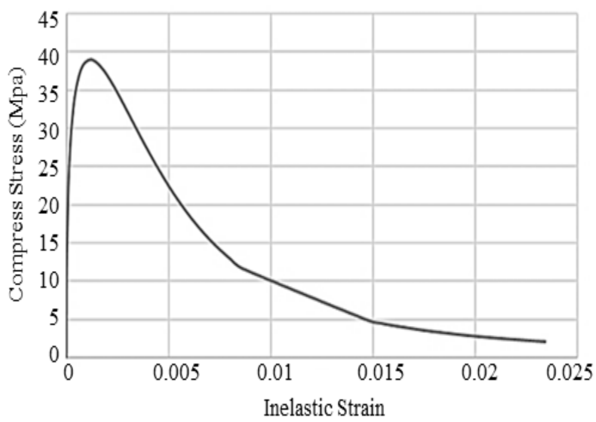

Fig. 9 (a) Compressive stress vs. Inelastic strain

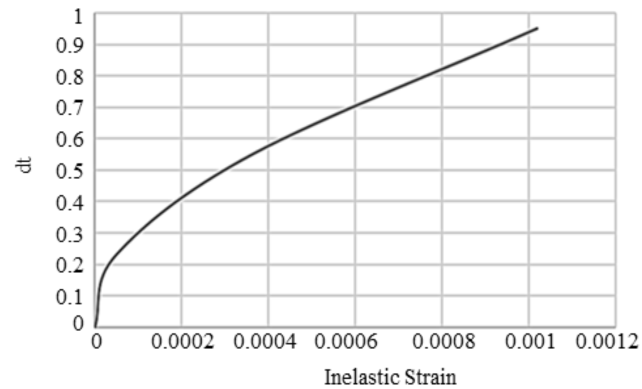

Fig. 9 (d) Tensile damage vs. Cracking strain strain

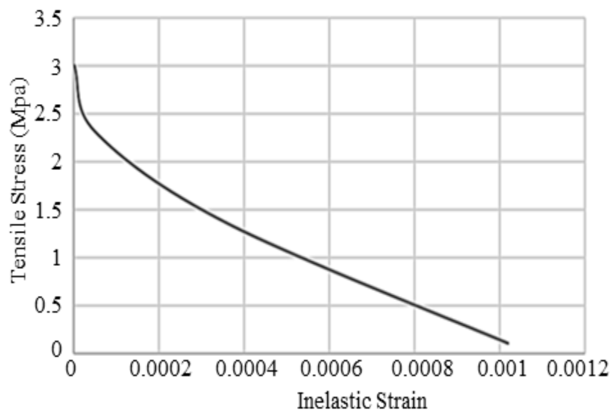

Fig. 9 (b) Tensile stress vs. Cracking strain

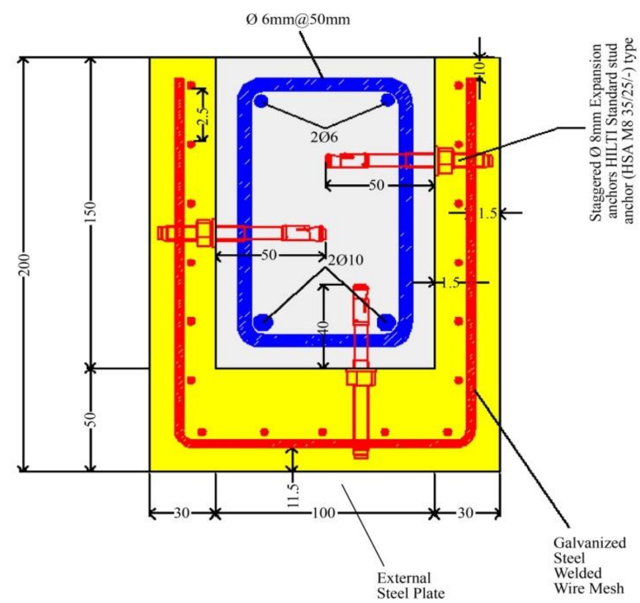

Fig. 10 Proposed beam Section strengthened using both SWM SCC and external steel plate (GABS and GBBS)

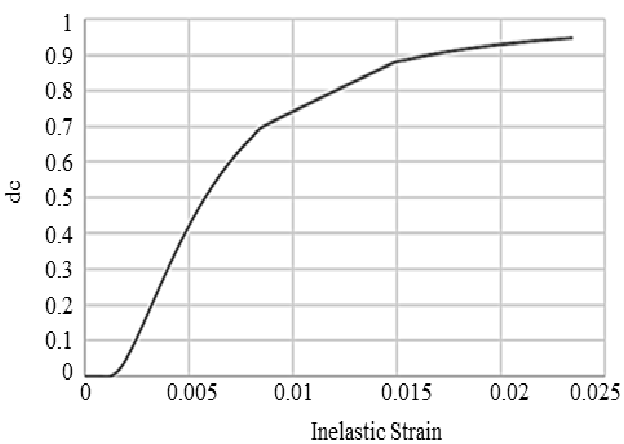

Fig. 9 (c) Compressive damage vs. Inelastic strain

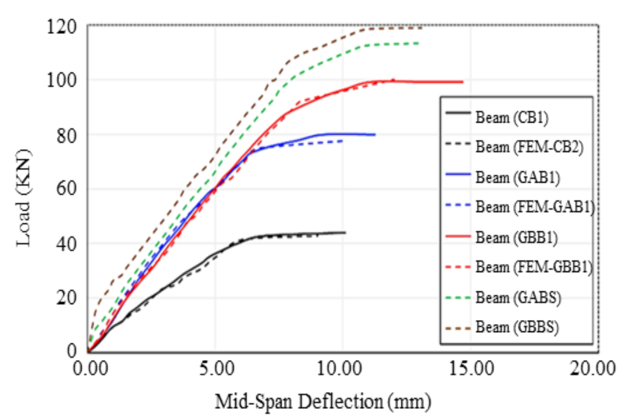

Fig. 11 Load-deflection curves for all beams (Experimental and FE results)

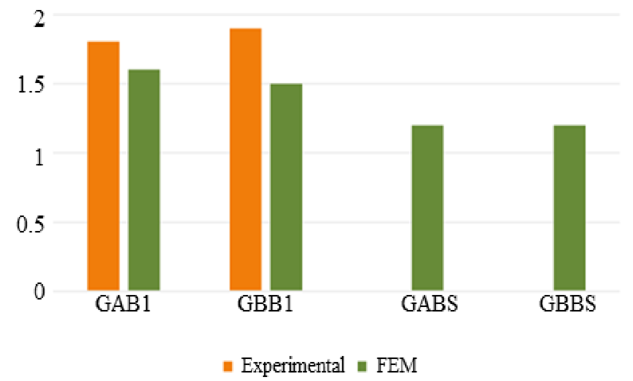

Fig. 12 Ductility index values for all studied beams (Experimental and FE results)

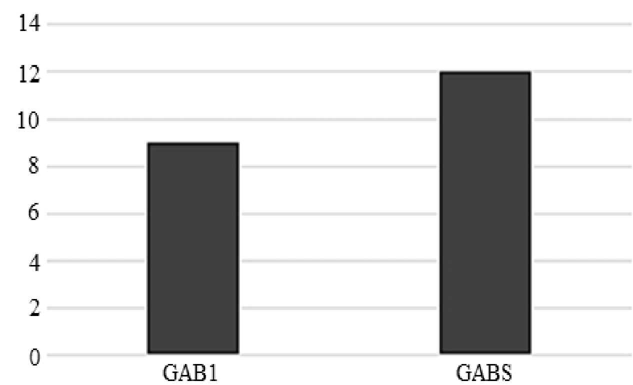

Fig. 13 Stiffness ratio for different techniques compared to the control beam

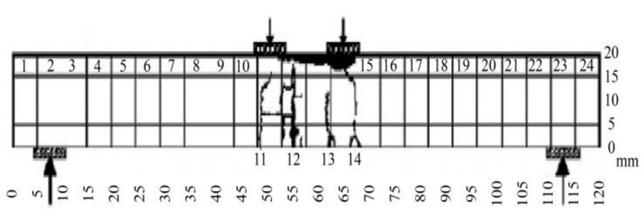

Fig. 14 (a) Experimental crack pattern for all tested beams

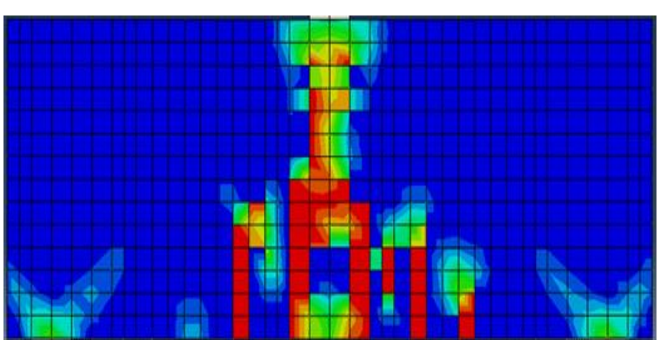

Fig. 14 (b) FE crack pattern from ABAQUS for GAB1 and GBB1 beams

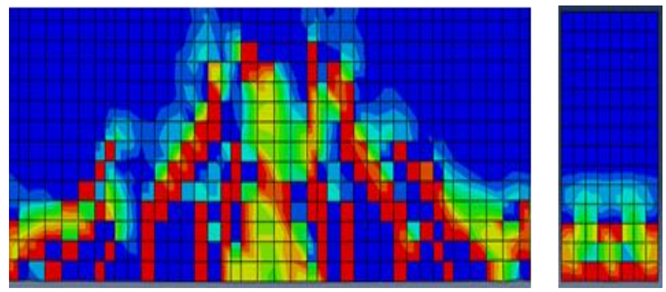

Fig. 15 FE crack pattern from ABAQUS for GABS and GBBS beams

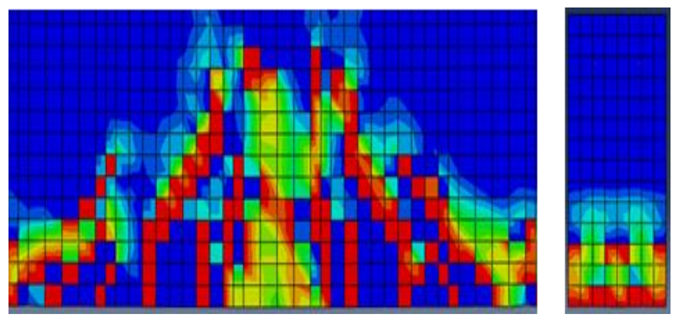

Fig. 16 Effect of steel plate thickness

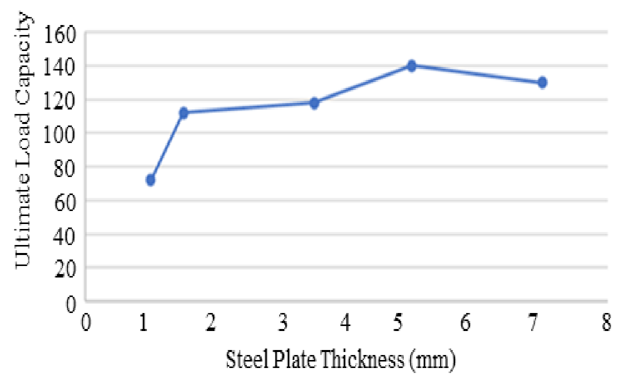

Fig. 17 Maximum load capacity for different plate thickness values

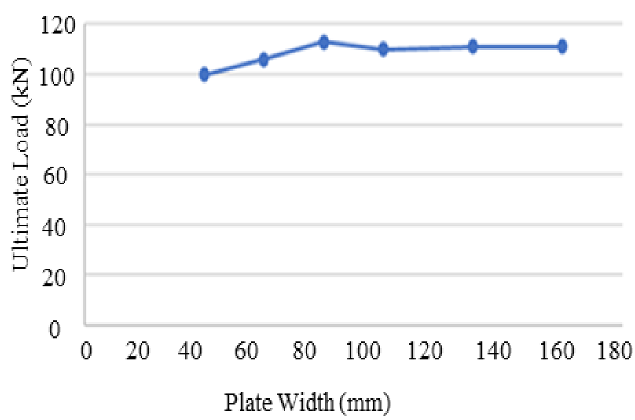

Fig. 18 Effect of plate width on results

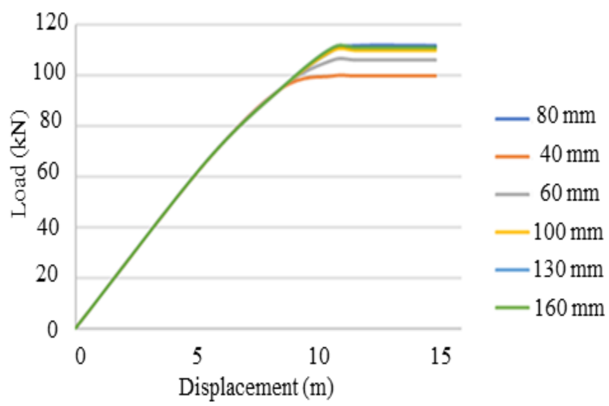

Fig. 19 Load displacement curves for different plate width values

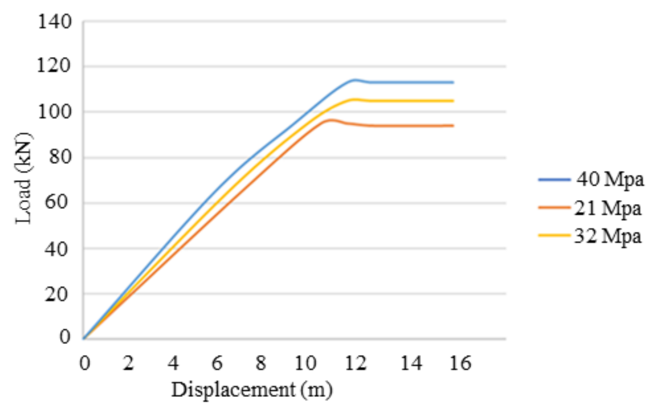

Fig. 20 Effect of concrete compressive strength Fc'

6. Conclusion

The conclusions of this study can be cast in the following points:

- The first group of strengthened beams (using SWM SCC only) restored 110% of the original control beams' load capacity, whereas the second strengthened group resorted to 163% on average.
- The FE results showed that the strengthened jacketed samples (with SWM SCC in addition to an external steel plate) restored, on average, 150 % and 172 % of the original control beams' load capacity for groups A and B, respectively.
- The three-dimensional FE model shows a good agreement with the experimental results in terms of the mechanical behaviour as well as the failure modes.
- Using an external steel plate as an assistant strengthening technique for the RC beams strengthened using SWM SCC jacketing changes the failure mode from ductile failure mode by flexural cracks into brittle one by large diagonal shear cracks.
- Using an external steel plate slightly increases the stiffness and decreases the ductility of the tested beams. Even though it increased the ultimate load capacity of the strengthened beams with SCC.

A parametric study was conducted on the RC beams strengthened with an extra steel plate:

- The maximum load capacity was found when the thickness was 5 mm; when the thickness is increased over 5 mm, the stiffness is increased, while the ultimate load capacity is decreased significantly due to the early failure of RC beams.
- The variation of the steel plate width does not affect the ultimate load capacity and stiffness values of the repaired RC beams.
- Using 40 MPa concrete strength will give the highest stiffness and load capacity values with an increase of 25 % compared to Fc'=32 MPa.

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