



## REHABILITATION OF ELLIPTICAL PARABOLIC REINFORCED CONCRETE SHELLS WITH OPENINGS

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### ABSTRACT

As the using of reinforced concrete shells structures with opening have many advantages that they permit to cover large area without using intermediate supports. They have light weights and require minimum amounts of material that it is required small thicknesses comparing to their spans. This investigation is carried out to study the efficiency of repair and strengthening of elliptical paraboloid reinforced concrete shells, which loaded by four concentrated loads at the center of the opening. An experimental program of several different techniques in repair and strengthening is executed. The materials, which are considered for strengthening, are; Glass fiber reinforced polymers GFRP at different position of the shell bottom surface, steel strip and external tie. The initial and failure loads as well as the crack propagation for the tested shells at different loading stages, deflections and failure load for repaired and shells are recorded. A non-linear computer program based on finite element techniques is used to study the behavior of these types of shells. Geometric and materials nonlinearities are considered in the analysis. The efficiency and accuracy of computer program are verified by comparing the program results with those obtained experimentally for the control shell with opening and strengthened shells.

**Keywords:** Shell; opening; repair; strengthening; GFRP-wrap; reinforced; concrete.

### 1. INTRODUCTION

Shells can cover large areas using a few numbers of supports and reduce cost compared to the other reinforced concrete systems. They are curved and warped or folded surfaces whose thicknesses are small compared to their other dimensions. Shells are highly efficient structures that possess several merits over conventional engineering structures of linear geometrical shapes [1]. Shell structures of different shapes and materials are widely applied

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to serve many purposes. Shells are found in many industrial and engineering products such as pipes, piles, dams, tunnels, off-shore structures, chimneys, towers, bridges, storage tanks and pressure vessels. The first reinforced concrete shells were constructed about the year 1910. The Zeiss - Dywidag type of cylindrical shell appeared about 1925, and the number of these structures in existence is very large [2].

Concrete is the most widely used material in shell construction; however other materials have also been used such as welded steel plates, metal decking, plywood, multiple layer timber decks, and fiberglass-reinforced plastic.

Defects which may appear due to unexpected conditions such as over loading, mistakes in design or construction will need suitable repair or strengthening techniques.

Radial shearing forces and moments and thus is the basis of the subsequent theoretical developments, but these equations did not be used in the practical fields until progress is done in the design methods of reinforced concrete structures [3, 4]. Love's equations did not be used till Carl Zeiss used these equations in the designing of a small reinforced concrete shell roof in 1924 in Jena, Germany. Since then many writers introduced several developments to shell theory aiming to simplify the procedures of shell analysis [3-6].

Beam method is a method which applied only to long shells [6]. The shell is assumed to act as a beam spanning longitudinally between the same supports. Since that time this method has gained popularity between the design engineers because it gives a clear and simple picture of the behavior of the shell, and because it is easy to check. The preliminary design is usually carried out by this method to obtain the approximate dimensions before carrying more calculations by the exact methods.

The earliest application of the finite element method on reinforced concrete shells is performed at 1967 [7]. In 1968, nonlinear material properties are introduced by Nilson [8], and an incremental loading technique is introduced to account for these nonlinearities. The solution is stopped when an element indicated a tensile failure, by this method Cracking is accounted for, and hence redefining a new cracked structure, which is again input into the computers reloaded incrementally. The results are checked by experimental tests. Plane stress studies are conducted for reinforced concrete structures which include elastic plastic behavior in compression as well as tensile cracking using initial stress approach [9].

Studies of reinforced concrete slabs by the emitted element method are used a progressive cracking procedure with some semi empirical moment curvature relationship [10]. Finite element method for studying prestressed concrete nuclear reactor pressure vessels treated as ax-symmetrical solids [11].

A general method of analysis which could analyze reinforced concrete slabs of arbitrary geometry and free-form shells under dead loads and monotonically increasing live loads. A layered triangular finite element taking account of the coupling effect between the bending action and the membrane action and he used an incremental loading procedure for the nonlinear analysis. The cracking of the concrete, the tension stiffening effect of concrete between cracks, and the nonlinear stress strain relationships for the concrete and steel reinforcement as considered nonlinear effects, Lin [12].

The behavior and strength of three similar reinforced concrete shells under uniformly distributed loads till a definite stage of deflection, and three different techniques have been taken to repair such cracked shell. Deflection, longitudinal strains, cracking and carrying capacities of the cylindrical shells prior to cracking and after repaired are recorded, and the

adequate repair system is recommended, Kamal et al. [13].

A research in a structural analysis process and rehabilitation approach for damaged, pneumatically formed reinforced concrete shell is performed by Foraboshi et al. [14]. The process is applied to a seriously damaged, large span, slender shell. Special nonlinear finite element modeling is used with doubly curved and multilayer elements. Security conditions of the reference shell, including buckling collapse and damage time evolution, are analyzed; the shell exhibited unsafe behavior. The rehabilitation approach is explained in that research also prediction of the model is compared with experimental in situ tests and good agreement between both is obtained [14].

A description of an adaptive calculation scheme for nonlinear (elasto-plastic) finite element (FE) analysis is conducted by Lackner et al. [15]. The adaptation of the FE mesh is performed by means of the h-version of mesh refinement. Before restart of the analysis after mesh refinement, the transfer of variables from the old to the new mesh must be performed. Unlike as for commonly used transfer schemes, the presented mode of transfer employ stresses and displacements for the evaluation of the state variables for the new mesh [15].

Fiber wraps are more efficient than steel strips and one layer of carbon fiber reinforced plastics wrap gave the same results as four layers of glass fiber reinforced plastics wrap. They concluded also that the repairing by changing the structural system (by adding ties) is more efficient than repairing by any other repairing techniques that it increases the initial cracking load by about 100% and the failure load by about 250% with respect to the control shells and deflection values are also decreased in different stages of loading and the failure shape in shell in case of using ties occurs at the middle of the side edge while in the other shells occurs mainly at the corners beside the supports and the computer program used provides results close enough to the experimental results for control and strengthened shells [16].

In this research, the efficiency of different repair and strengthening techniques for reinforced concrete shells with openings are studied and compared experimentally and analytically.

## 2. RESEARCH SIGNIFICANCE

This study is carried out to investigate the behavior of shells under the effect of loads before and after repair and strengthening processes. The feasibility of using different advanced repairing and strengthening materials and techniques to rehabilitate reinforced concrete elliptical paraboloid shells with openings are studied. A nonlinear computer program based on the finite element techniques applied to study the behavior of shells. The main variables in this investigation are; repairing and strengthening materials and techniques. Failure loads, deflections at different loading stages as well as propagation of cracks for the tested shells are recorded.

The importance of this research is based on the need to know the available data addressing the behavior of elliptical paraboloid reinforced concrete shells as well as introduces different techniques for their repairing or strengthening. This research provides data for researchers concerning the behavior of elliptical paraboloid reinforced concrete shells and their rehabilitation.

### 3. EXPERIMENTAL PROGRAM

The conducted experimental program includes the tests carried out on different materials used either for casting the reinforced concrete shells with and without openings as well as the repairing and strengthening materials. Tested samples are shown in Table (1).

Table 1: Concrete mix used.

Cement ( $kg/m^3$ )	W/C	Sand ( $kg/m^3$ )	Crushed dolomite ( $kg/m^3$ )	Slump (mm)	$F_{cu7}$ ( $kg/cm^2$ )	$F_{cu28}$ ( $kg/cm^2$ )
350	0.5	588.3	1176.6	80	230	340

#### 3.1. Concrete Materials

The cement used was the ordinary Portland cement, which was provided from the Suez factory in Egypt. A crushed dolomite with a maximum nominal size of 12 mm, graded sand with a fineness modulus of 2.42 and tap water are used to produce the used concrete mix of shell samples as shown in Table (1). The steel used in this experimental work is the normal mild steel (St.240/370) as a welded mesh of rounded plain bars, 4.2 mm diameter. Yield stress, ultimate strength, modulus of elasticity and elongation were obtained by performing different tests. Test results are given in Table (2).

Table 2: Test results of steel reinforcement.






Steel Type	Yield Stress ( $kg/cm^2$ )	Tensile Strength ( $kg/cm^2$ )	Elongation (%)	Modulus of Elasticity ( $t/cm^2$ )
Mild steel	3000	4100	21.9	2020

#### 3.2. Concrete Shells

Nine simply support reinforced concrete elliptical parabolic (Elpar) shells with openings are cast then, divided in to three groups. The first is control shell without openings "C" and the other is control shell "CO" with central opening 20 x 20 cm. The second group is strengthened using four different methods. The third group is preloaded up to 67% of failure load then repaired using three techniques. Shell samples are shown in Figs. (1) and (2) and Table (3).

Shells are tested under concentrated loads as shown in Fig. 3. The repaired and strengthened shells are tested by loading them up to failure load under the same first loading conditions to study the behavior and the efficiency of repairing techniques. The procedures of repair and strengthening techniques are recorded and photographed. Results of deflection for each load increments, the first cracking and failure loads are recorded. The shape and the pattern of cracks are traced for each load increments up to failure before and after the repair process. Then the tested shells are photographed to show the crack pattern.

Table 3: Tested shell samples.

Case	shell code	Description	Dimensions (mm)	reinforcement	Preloading value
Control	C	Control shell without opening	1200x1200x40		--
	CO	Control shell with central opening			--
Strengthened shells	SOG1	strengthened by using two layers of glass fiber reinforced polymers GFRP wraps (Type 1) 	1200x1200x40 mm with a central opening 200x200	Bottom Steel mesh 40x40 Ø 4 mm	Preloaded up to $2/3 F_{cu}$
	SOG2	strengthened by using two layers of glass fiber reinforced polymers GFRP wraps (Type 2) 			
	SOG3	strengthened by using two layers of glass fiber reinforced polymers GFRP wraps (Type 3) 			
	SOT	Strengthened by using external tie			
	Repaired shells	ROG1			
ROG2	repaired by using two layers of glass fiber reinforced polymers GFRP wraps (Type 2) 				
ROS	repaired by using one layer of steel plate 				

Increasing symbol "F" referring to slabs analyzed by FE model such as "COF", "SOG1F", "SOG2F", and "SOG3F".

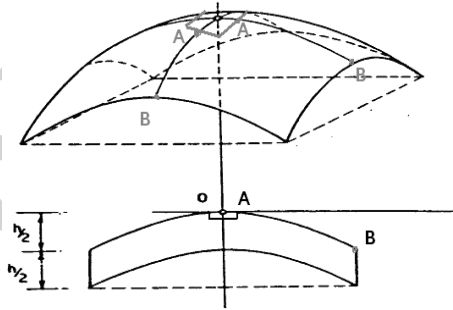


Figure 1. The plane of elliptical paraboloid shell with central opening 0.2m x 0.2m.



Figure 2. Control shell "CO" with central opening.



Figure 3. The arrangement of the hydraulic jack which applying the load.

The behavior of the materials used as well as repair and strengthening materials are estimated from the results recorded during testing of reinforced concrete shells like initial crack, deflection at each load increment at the center of opening edge at point (A) of the lower surface of each shell and at the point of the center of external edge of the shell at point (B) on the lower surface, ultimate load, crack propagation which are recorded at each stage of loading.

### 3.3. Repair and Strengthening Materials

**Steel Strips:** Mild steel (St. 240/370) plates of dimension 100x12x0.15 cm were used. The mechanical properties are shown in Table (4). The Sikadur-31CF adhesive, as shown in Table (5), was used to fix the steel plates to the lower surface of shell.

Table 4: Mechanical properties of steel strips (St. 240/370).

Steel Type	Yield Stress ( $kg/cm^2$ )	Tensile Strength ( $kg/cm^2$ )	Elongation (%)	Modulus of Elasticity ( $t/cm^2$ )
Mild steel	3000	4100	21.9	2020

**Steel Resin Matrix:** Sikadur-31CF is a solvent-free, thixotropic, two components adhesive and repair mortar, based on a combination of epoxy resins and specially selected high strength fillers. The resin complies to the requirements of ASTM C881-78 type 1, Grade 3 Class B+C. Sikadur-31CF is available in three different grades of reactivity: rapid, normal, long pot life. Its mechanical properties are shown in Table (5).

Table 5: Mechanical properties of Sikadur-31CF (as provided by manufacturer).

Property	Value
Compressive strength	600 - 700 $kg/cm^2$
Adhesive strength on steel	150 -200 $kg/cm^2$
Adhesive strength on concrete	35 $kg/cm^2$ (concrete failure)
Modulus of elasticity	43000 $kg/cm^2$



**E-Glass Fiber Reinforced Polymer Wrap (GFRP-wrap) System:** This system is all externally applied for strengthening and repairing of structural members. A locally available woven roving glass fiber fabric was used. Fiber used in this system is E-glass fiber. This glass fiber fabric is available in a package of woven roving glass fiber fabric with length equal or more than 50 m ( $L \geq 50\text{m}$ ). Design thickness of the glass fiber is 0.17 mm based on the total area of E-glass fibers and these fibers are available in 1- m width roll. The aerial weight is  $450 \text{ gm/m}^2$  to save easy handle and use. The GFRP is used for repair and strengthening of reinforced concrete structures, temper and brickworks for the purposes like changes of use or repair of defects also prevention of defects. Strengthening techniques are shown in Figures (4) to (6). Its main properties are shown in Table (6).



Figure 4. Shell "SOG1" strengthened using 2-layers of GFRP wrap (Type 1).



Figure 5. Shell "SOG2" strengthened using 2-layers of GFRP wrap (Type 2).



Figure 6. Shell "SOG3" strengthened using 2-layers of GFRP wrap (Type 3).

Table 6: Properties of glass fiber wrap GFRP-wrap (*as provided by manufacturer*).

Property	Value
Fabric length/Roll	> 50 m
Fabric width	100 cm
Fabric design thickness	0.10 mm
Areal weight	0.45 kg/m <sup>2</sup>
Tensile strength of fibers	22500 kg/cm <sup>2</sup>
Modulus of elasticity of fibers	700 t/cm <sup>2</sup>
Strain at failure of fibers	3.17%

**GFRP-wrap Resin Matrix:** Isophthalic polyester belonging to the Vipel<sup>®</sup> F737 series resins produced by AOC, USA was used. The resin is suitable for various fabrication processes such as hand layup, winding and pultrusion and extensively used in fabricating water pipes and other corrosion resistance applications. This resin matrix is available in a pre dosed units (A + B) with a weight of 5 Kg with a shelf time about 18 months from manufacturing date in original packing stored at temperatures from +5°C to +25°C. The pot life of the mixture are 15°C: 90 min. (5 kg) and 35°C:30 min (5 kg) where as the open time is 30 min. (at +35°C). Application temperature is ranged from +15°C to + 35°C of the ambient atmosphere. The resin has excellent mechanical properties in terms of tensile strength (86 MPa), tensile modulus (3.4 GPa) and tensile elongation (4.0%) according to ASTM D638 test method and has a specific gravity of 1.12 as reported by the manufacturer.

#### 3.4. Repairing and Strengthening Methodology

The strengthening procedures using GFRP-wrap are executed in three types; type 1 as shown in Figs. (4), type 2 as shown in Fig. (5) and type 3 as shown in Fig. (6). A strengthening technique by using external tie is shown in Fig. (7). The repairing procedures using GFRP-wrap are executed in three types; type 1 as shown in Figs. (8), type 2 as shown in Fig. (9) and repairing using steel plate as shown in Fig. (10).

The application of the GFRP wraps was performed according to the following



procedures: the tension side of the reinforced concrete shell was roughened and prepared by removing any loose materials or dirt using compressed air. The GFRP wraps were cut into 10 cm width strips with a length of 100 cm (the width was 10 % of the span) then the adhesive polymer was mixed and then applied to the tension surface using a rolling brush and the wraps were placed and pressed by hand to saturated with the resin. The second layer was bonded in this manner and then the shells were left for eight days until tested to ensure complete hardening of the resin according to the guidelines of the manufacturer.

Another strengthening configuration utilizing external steel ties was examined used as a stiffener for the shell supports as shown in Fig. (7). The ties were made of steel angles (50x50x5 mm), welded together to form a square frame stiffened at corners by welding a 2 mm steel plate at the corners. The frame dimensions were 120.3x120.3 cm. The shell rested on this frame at the four supports then tested.

The use of steel plates in repair works was performed using 1.5mm thick steel plates re cut into strips of dimension 100 cm and 10 cm width as shown in Fig. (10). The tension surface of the shell was prepared as indicated before and the steel strips were adhered to the tension surface of slabs by using the epoxy resin. Uniform pressure on the steel plates was applied until hardening of the resin. Steel bolts were used to grip the steel strips to the slab at 10 cm intervals and the shells were left for 10 days to cure.

The efficiency of different materials used in repair and strengthening of reinforced concrete shells depends mainly on the material behavior. The efficiency can be expressed by deflection, initial cracking load, and failure (ultimate) load, mode of failure and crack behavior.



Figure 7. Shell strengthened by using external tie "SOT".

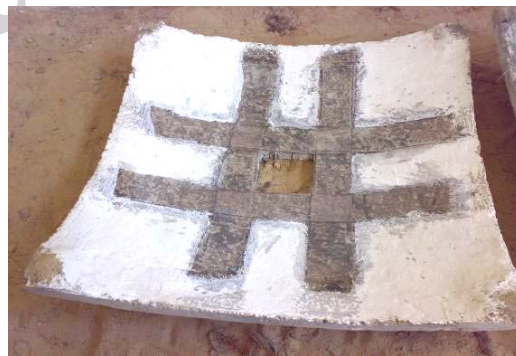


Figure 8. Repaired shell "ROG1" by using 2-layers of GFRP wrap (Type 1).



Figure 9. Repaired shell "ROG2" by using 2-layers of GFRP wrap (Type 2).



Figure 10. Repaired shell "ROS" by using steel strip.

#### 4. FINITE ELEMENT ANALYSIS

Several researchers [3, 7-10, 12 and 15] have studied the nonlinear analysis of shells. A nonlinear computer program based on the finite element techniques applied to study the behavior of shells. Geometric and material nonlinearities have been considered. The material nonlinearities are taken into consideration. The nonlinearities include the stress-strain relationship for concrete and steel reinforcement, concrete cracking and tension stiffening effects. The efficiency and accuracy of the computer program are verified by comparing its results with the experimental results.

A nonlinear finite element FE computer program performed by (Meleka, 1995) [17] is used. In the nonlinear finite element computer program, for each node of the finite element mesh there are five degree of freedom, three displacements in X,Y and Z directions and two rotations about X and Y axis. Boundary conditions which are taken in consideration are as follows; The shell is assumed to support on three nodes for each corner. Finite element mesh is  $12 \times 12$  elements as the dimensions of the tested shell are  $120 \times 120$  cm as shown in Fig. (11). Every direction is consists of 12 elements of 10 cm length for each as shown in Fig. (12).

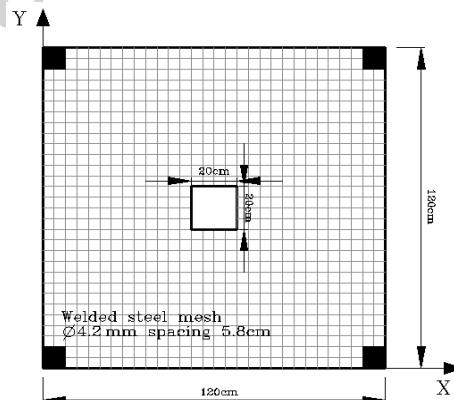
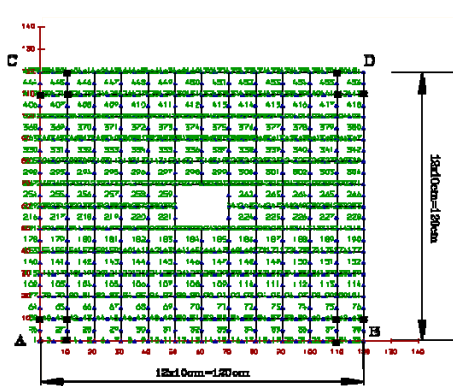
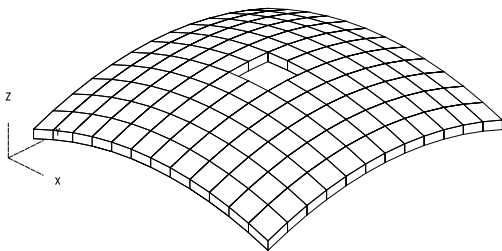


Figure 11. Dimensions and reinforcement of the shell.

For support (A), nodes "3","39","41" is restrained only in X and Z directions while free in Y direction also the rotation about Y axis is permitted. At support (B), node "23","61","63" is restrained only in X and Z directions while free in Y direction also the rotation about Y axis is permitted. At support (C), node "419","421","459" is restrained in X, Y, and Z direction also the rotation about X and Y axis is permitted. At support (D), node "441","443","479" is restrained in X, Y and Z directions also the rotation about X and Y axis is restrained as shown in Figures (12) and (13).

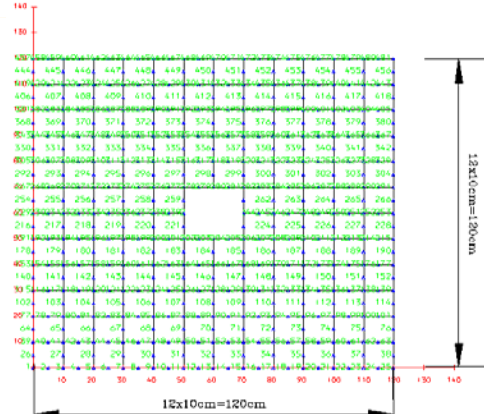


(a) In plan.

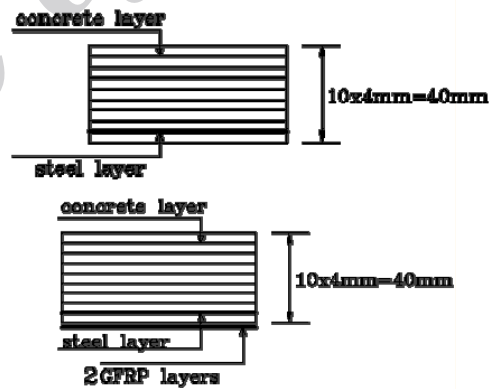


(b) In 3-dimensions (120cm x120cm).

Figure 12. Finite element mesh 12x12



(a) Finite element mesh.



(b) Layered system for control and strengthened.

Figure 13. Finite element meshes and layer system for model.

The control shell "CO" is analyzed by the computer program based on the nonlinear finite element analyses which based on the nonlinear finite element method. It named "COF". The dimension of this tested shell is 120×120×4cm is supported on its four corners. The reinforcements are a welded steel mesh of diameter  $\phi$  4.2 mm and the spacing between bars is 5.8 cm in each direction. A concentrated load is divided in to four concentrated loads applied at the four edges of the opening of shell. The load increment is applied by 250 kg up to failure. The material properties and dimensions are:

1. Height of the side curve parabola in both directions = 12.5 cm
2. Height of the crown at the center of the shell = 25 cm
3. Concrete compressive strength  $C_{28}=340\text{kg/cm}^2$
4. Modulus of rupture of concrete  $f_t = 35\text{kg/cm}^2$
5. Yield strength of steel  $f_y = 3000 \text{ kg/cm}^2$
6. Young's modulus of steel  $E_s=2.1 \times 10^6 \text{ kg/cm}^2$
7. Young's modulus of concrete  $E_c=2 \times 10^5 \text{ kg/cm}^2$
8. Poisson's ratio  $\nu = 0.2$
9. Concrete cover  $c = 0.5 \text{ cm}$

The properties of the strengthened shells SOG1, SOG2 and SOG3 are the same as before and the glass fiber reinforced polymer wrap GFRP-wrap properties are:

1. GFRP-wrap width  $z = 10 \text{ cm}$
2. GFRP-wrap thickness/layer = 0.1 cm
3. Tensile strength of GFRP = 22500 kg/cm<sup>2</sup>
4. Yield strength of resin = 2450 kg/cm<sup>2</sup>
5. Fibers modulus of elasticity=700000kg/cm<sup>2</sup>
6. Resin modulus of elasticity = 43000 kg/cm<sup>2</sup>
7. Young's modulus of GFRP = 210000 kg/cm<sup>2</sup>

The boundary conditions of strengthened shell is the same as given before but the layer system is arranged to simulate the effect of using two layers of glass fiber reinforced polymers wrap GFRP-wrap. To represent the addition 2 layers of GFRP wrap, the outer elements are considered to be with addition number of layers of the GFRP as shown in Fig. (13). Each layer had a 10 cm width and 0.1 cm thickness. They named as SOG1F, SOG2F and SOG3F.

## 5. TEST RESULTS

Load-deflection curves at point (A) of different strengthened shells compared to the control shell with central opening CO are shown in Fig. (14) while at point (B) are shown in Fig. (15). Load-deflection curves of different repaired shells at points (A) and (B) respectively are shown in Figures (16) and (17). Initial cracking loads and failure loads for each type of strengthened and repaired shells are shown in Figures (18) and (19).

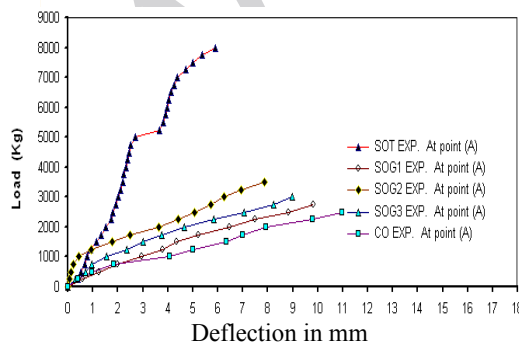


Figure 14. Deflection values of strengthened shells at point (A).

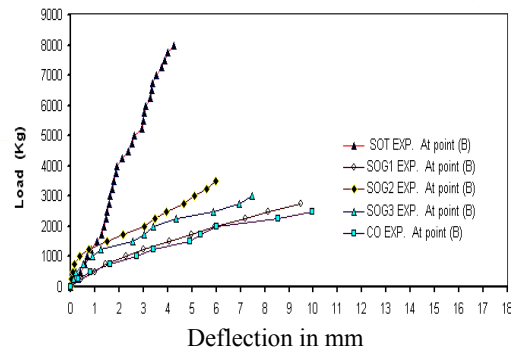


Figure 15. Deflection values of strengthened shells at point (B).

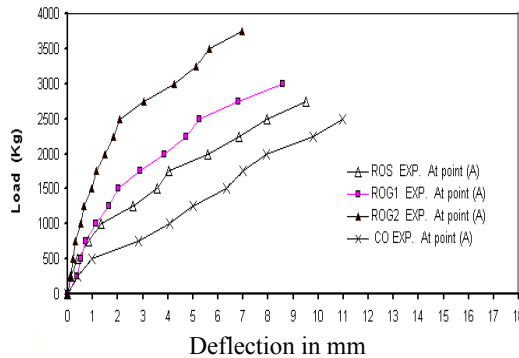


Figure 16. Deflection values of repaired shells at point (A).

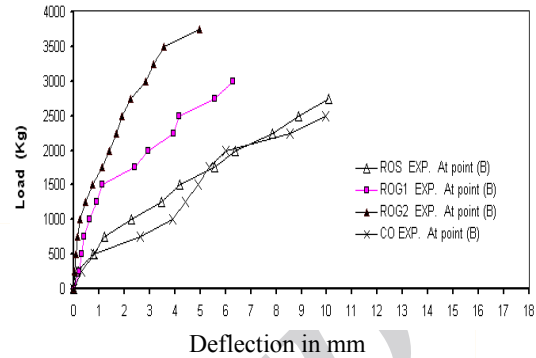


Figure 17. Deflection values of repaired shells at point (B).

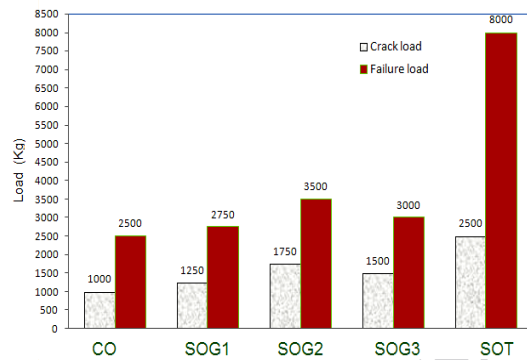


Figure 18. Initial cracking load and failure loads for strengthened shells.

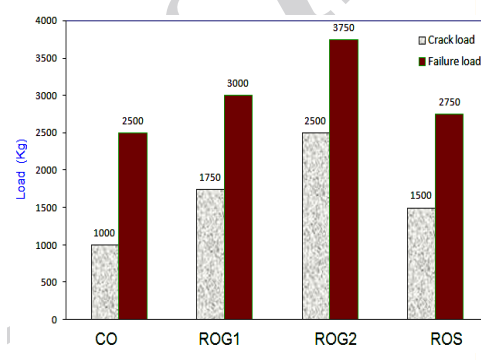


Figure 19. Initial cracking load and failure loads for control and repaired shells.

### 5.1. Deflection of Tested Shells

#### A- Deflections of Strengthened Shells

The behavior of the strengthened shells is improved in the used two different techniques. Deflections decreased in all stages of loading with respect to the control shell.

At the initial cracking load of the control shell CO, the deflections of the strengthened shell using external ties, SOT are decreased by 55.6% and 61.5% at point (A) and (B) respectively with respect to the control shell. At the ultimate load of the control shell, the deflections of the strengthened shell using external ties are decreased by about 46.3% and 53.5% at points (A) and (B) respectively.

For the second shell which is strengthened by using two layers of glass fiber reinforced polymers wraps GFRP-wrap (Type 1), SOG1, the deflection are decreased. At the initial cracking load of the control shell CO, at points (A) and (B) deflection are decreased by about 6.6% and 23.2% respectively, while at the failure load of the control shell CO, deflections are decreased by about 10.5% and 4.5% at points (A) and (B) respectively with respect to the control shell.

For the third shell which is strengthened by using two layers of GFRP-wrap (Type 2),



SOG2, the deflection values are decreased. At the initial cracking load of the control shell CO, at points (A) and (B) deflection are decreased by about 38.5% and 45.1% respectively, while at the failure load of the control shell CO, deflections are decreased by about 28.2% and 39.8% at points (A) and (B) respectively with respect to the control shell.

For the fourth shell which is strengthened by using two layers of GFRP-wrap (Type 3), SOG3, the deflection values are decreased. At the initial cracking load of the control shell CO, at points (A) and (B) deflection are decreased by about 25.5% and 34.2% respectively, while at the failure load of the control shell CO, deflections are decreased by about 18.3% and 24.8% at points (A) and (B) respectively with respect to the control shell.

#### *B- Deflections of Repaired Shells*

The behavior of the repaired shells is improved in the different repair techniques. Deflections decreased in the most stages of loading with respect to the control shell and increased in two readings only as following.

At the initial cracking load of the control shell CO, the deflections of the repaired shell using two layer of GFRP-wrap (Type 1), ROG1, is decreased at point (A) by 29.2% and it is decreased at point (B) by 38.5% with respect to the control shell CO, and at the ultimate load of the control shell, the deflections are decreased by about 21.8% and 36.7% at points (A) and (B) respectively.

For the second shell which is repaired by using two layers of GFRP-wrap (Type 2), ROG2, the deflections are also decreased. At the initial cracking load of the control shell CO, at points (A) and (B) deflections are decreased by about 50.4% and 52.1% respectively, while at the failure load of the control shell CO, deflections are decreased by about 36.7% and 50% at points (A) and (B) respectively with respect to the control shell.

For the third shell which is repaired by using steel plates ROS, at the initial cracking load of the control shell CO, the deflection value is decreased at point (A) by 12.5% but it is increased at point (B) by 6.2% with respect to the control shell CO, while at the failure load of the control shell CO, deflections are decreased by about 13.5% at point (A) but it is increased at point (B) by about 1.2% with respect to the control shell CO.

#### *5.2. Cracking Loads*

For all investigated reinforced concrete shells the cracking behavior and cracking patterns are improved by repair or strengthening. Cracking loads and failure loads of strengthened and repaired shells are recorded as shown in Figs. (18) and (19).

Figure (18) shows that, for the strengthened shell by using external ties SOT, the initial cracking load is increased by about 150% with respect to the control shell CO. For the second shell which is strengthened by using two layers of GFRP-wrap (Type 1), SOG1, the initial cracking load is increased by about 25% with respect to the control shell CO. For the third shell which is strengthened by using two layers of GFRP-wrap (Type 2), SOG2, the initial cracking load is increased by about 75% with respect to the control shell CO. For the fourth shell which is strengthened by using two layers of GFRP-wrap (Type 3), SOG3, the initial cracking load is increased by about 50% with respect to the control shell CO. previous result are in agreement with previous researches [15].

From Fig. (19) it is noticed that, the shell which is repaired by using two layer of glass fiber reinforced polymers wrap G-FRP (Type 1), ROG1, the initial cracking load is



increased by about 75% with respect to the control shell CO. In the shell which repaired by using two layer of GFRP-wrap (Type 2), ROG2, the initial cracking load is increased by about 150% with respect to the control shell CO.

In the shell which repaired by using steel plates ROS, the initial cracking load is increased by about 50% with respect to the control shell CO.

### 5.3. Crack Patterns

The crack patterns are recorded, illustrated and photographed at each load increment. The number of cracks is decreased in all cases of repair and strengthening used in this research in agreement with previous researches [15]. The improvement in the cracking behavior depends on the method of repair or strengthening. The crack pattern for all shells is shown in Figures (20) to (27).

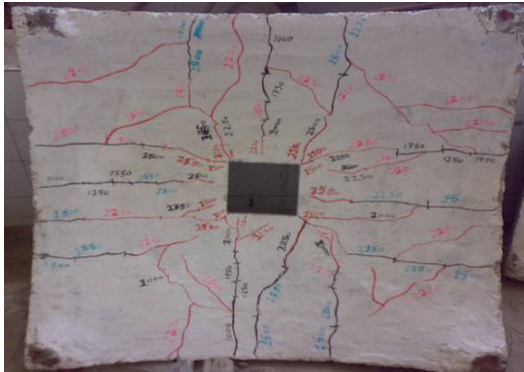


Figure 20. Crack pattern of the control shell "CO". [Failure load = 2500 kg]

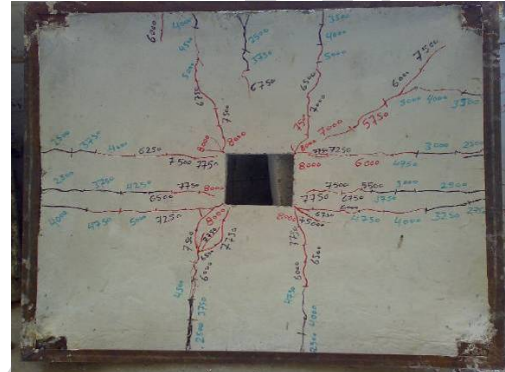


Figure 21. Crack pattern of shell strengthened by external tie "SOT". [Failure load = 8000 kg]



Figure 22. Crack pattern of shell "SOG1" strengthened by using 2 layers GFRP (Type 1). [Failure load = 3500 kg]



Figure 23. Crack pattern of shell "SOG2" Strengthened by using 2 layers GFRP (Type2). [Failure load = 3500 kg]



Figure 24. Crack pattern of shell "SOG3" strengthened by using 2 layers of GFRP (Type 3). [Failure load = 3500 kg]

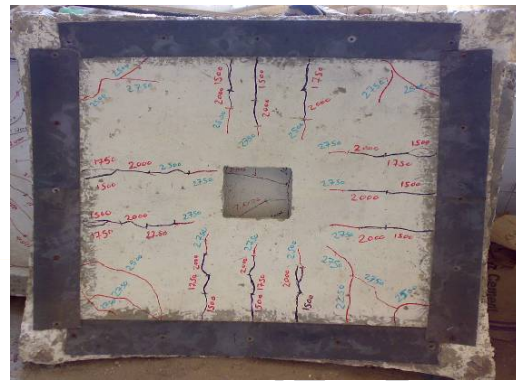


Figure 25. Crack pattern of shell "ROS" repaired by steel plate. [Failure load = 2750 kg]



Figure 26. Crack pattern of shell "ROG1" repaired by using 2 layers of GFRP (Type 1). [Failure load = 3000 kg]



Figure 27. Crack pattern of shell "ROG2" repaired by using 2 layers GFRP (Type 2). [Failure load = 3750 kg]

#### 5.4. Failure Loads for Strengthened and Repaired Shells

For strengthened shells the initial cracking loads and failure loads are shown in Fig. (18). For repaired shells the initial cracking loads and failure loads values comparing to control shell deflection are shown in Fig. (19).

The failure load of the shell which is strengthened by using external ties SOT is increased by about 220% with respect to the control shell CO as noticed in Fig. (18).

For the second shell which is strengthened by using two layers of glass fiber reinforced polymers wraps G-FRP (Type 1), SOG1, the failure load is increased by about 10% with respect to the control shell CO. For the third shell which is strengthened by using two layers of GFRP-wrap (Type 2), SOG2, the failure load is increased by about 40% with respect to the control shell CO. For the fourth shell which is strengthened by using two layers of GFRP-wrap (Type 3), SOG3, the failure load is increased by about 20% with respect to the control shell CO. All previous results indicated that, the strengthened shells are carrying extra loads compared to the control shells.

From Fig. (19), it is noticed that the shell which is repaired by using two layer of GFRP-

wrap (Type 1), ROG1, failure load is increased by about 20% with respect to the control shell CO. In the shell which repaired by using two layer of GFRP-wrap (Type 2), ROG2, the failure load is increased by about 50% with respect to the control shell CO. In the shell which repaired by using steel plates ROS, the failure load is increased by about 10% with respect to the control shell CO. All previous results indicated that, the repaired shells are carrying extra loads compared to the control shells.

### 5.5. Comparison between Finite Element Analysis and Experimental Results

The control shell CO is analyzed using FE and named as COF. The shell strengthened by using 2 layer of glass fiber reinforced polymers wrap GFRP (type 1→ SOG1), (type 2→ SOG2) and (type 3→ SOG3) is analyzed by the FE computer program based on the nonlinear finite element analyses and named as SOG1F, SOG2F and SOG3F respectively. The obtained results are compared with the experimental results. Test results are shown in Figures (28) to (31). The results of the nonlinear analysis come close to the experimental results. Results of FE analysis are nearly in agreement with (Bashandy, 2004) [7].

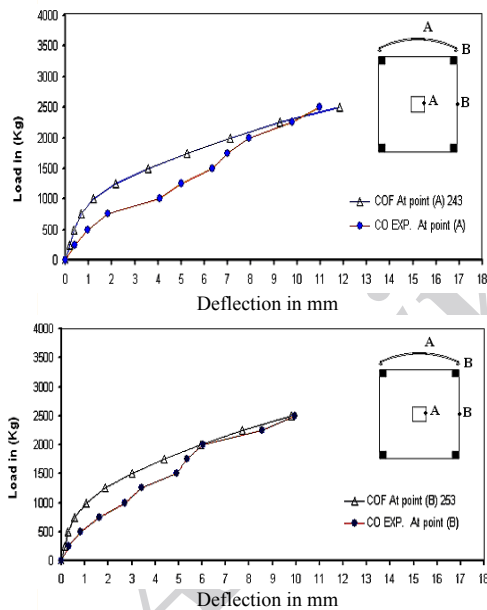


Figure 28. Deflection values of control shell [CO] compared to FE model [COF] at points (A) and (B).

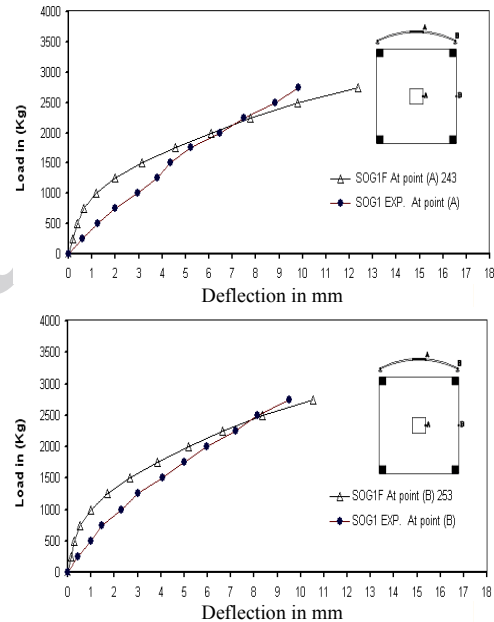


Figure 29. Deflection values of strengthened shell [SOG1] compared to FE model [SOG1F] at points (A) and (B).

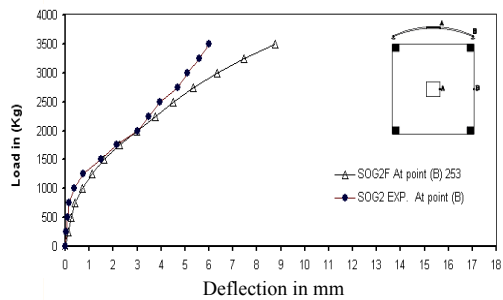
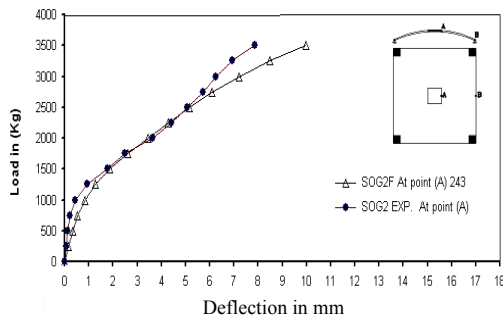


Figure 30. Deflection values of strengthened shell [SOG2] compared to FE model [SOG2F] at points (A) and (B).

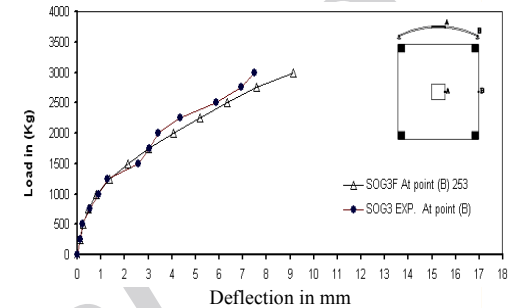
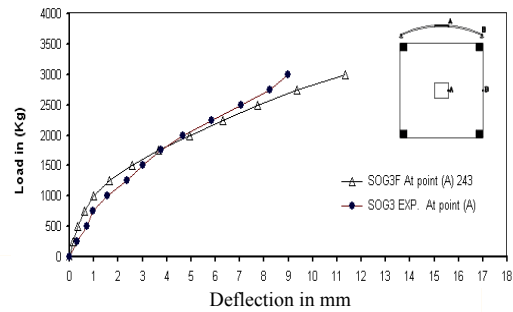


Figure 31. Deflection values of strengthened shell [SOG3] compared to FE model [SOG3F] at points (A) and (B).

## 6. CONCLUSIONS

Based on the available research results, the following main conclusions for the repairing and strengthening of reinforced concrete elliptical paraboloid shells as follows:

1. The using of shells without any opening is more efficient than using shell with a central opening as the failure load increased by about 14%.
2. The behavior of the strengthened shells is improved in the used two different techniques. Deflections decreased in all stages of loading with respect to the control shell.
3. The technique suggested in this research which depends on using fiber reinforced polymer wraps increase the value of the initial cracking and failure loads and decrease the deflection in repaired shells compared to control shell.
4. Using of fiber reinforced polymer GFRP wrap is more efficient than using steel strips because GFRP provides higher rigidity and easier in applying and adhering.
5. Use of fiber reinforced polymer GFRP wrap in diagonal direction is better than using it around the opening only as the failure load increased by about 10 %.
6. Use of fiber reinforced polymer GFRP wrap around the opening and external edges is better than using it around the opening only because failure load increased by about 20 %.
7. Using steel plate enhances the ultimate load by about 10%.
8. Using external tie decreases the deflection values by about 55-60% and increases the initial cracking load by about 150% and ultimate load by about 220%.
9. The suggested FE model for strengthening shells is quite accurate in representing the



problem.

10. The developed FE computer program can be applied to study different cases of strengthening that are not included in this experimental program with and without openings.

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