Behavior of Reinforced Height Strengthened Concrete one Way Slabs Strengthened with CFRP Sheets

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ABSTRACT

The principal objective of this paper is the investigate of experimental and theoretical flexural behavior reinforced height strength concrete one-way slabs strengthened or repaired with externally bonded carbon fiber reinforced polymer (CFRP) sheets. The experimental work includes testing of nine reinforced concrete slab specimens with dimensions (1700mmx300mmx100mm), six of these slabs were strengthened, two slabs were repaired with carbon fiber reinforced polymer (CFRP) strips and one specimen was tested without strengthening as reference (control) slab for comparing the performance of CFRP strengthened or repaired slabs. The experimental variables considered in the test program include the location, quantity, shape and dimensions of CFRP sheets. All the reinforced concrete slab specimens were designed of the same dimensions and reinforced identically to fail in flexure. All slabs had been tested in simply supported conditions subjected to central concentrated load. The experimental results show that the ultimate loads are increased by about (8-64%) for the slabs strengthened with bonded CFRP sheets with respect to the unstrengthened reinforced concrete slab (control slab). Three-dimensional nonlinear finite element analysis has been used to conduct the numerical investigation of the general behavior of strengthened slabs. **ANSYS** (Version 13.0) computer program was used in this work. Eight-node brick elements (SOLID65) are used to represent the concrete and three dimensional shell elements (SHELL 41) are used to represent the CFRP strips in the finite element analysis model. Perfect bond between the concrete surface and the bonded CFRP sheets is assumed.

التقصي العملي والنظري للسلوك الانشائي للبلاطات الخرسانية العالية المقاومة المسلحة و المقواة بصفائح البوليمر المسلح بالألياف الكربونية

المقدمة

ان الغرض من هذا البحث هو تقديم دراسة عملية و نظرية لسلوك الانحناء للبلاطات الخرسانية المسلحة ذات الاتجاه الواحد والمقواة او المعاد تصليحها بأشرطة الياف الكاربون البوليمرية (CFRP). يتضمن الجزء العملي من هذا البحث فحص تسعة نماذج لبلاطات خرسانية مسلحة مختبرياً بابعاد (1700ملم طول، 300ملم عرض، 100 ملم سمك البلاطة) بالاضافة الى سلسلة من الفحوصات على المواد الانشائية المستخدمة. سته من هذه البلاطات الخرسانية المسلحة تم تقويتها و اثنان من هذه البلاطات تم اعادة تصليحها باستخدام اشرطة الياف الكاربون البوليميرية (CFRP) وبلاطة خرسانية مسلحة واحدة تم فحصها بدون أي تقوية واعتبرت كنموذج اساس لغرض المقارنة مع النماذج المقواة او المعاد تصليحها. ان المتغيرات الاساسية التي جرى أعتمادها في

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الجانب العملي هي موقع، كمية، شكل وابعاد اشرطة الياف الكاربون البوليمرية المستخدمة في تقوية او تصليح هذه البلاطات. صممت جميع البلاطات الخرسانية المستخدمة في هذا البحث بنفس الابعاد وتم تسليحها بنفس كمية حديد التسليح بشكل يضمن فشلها بالانحناء، تم فحص جميع البلاطات في فضاء بسيط الاسناد وبتسليط حمل مركز في منتصف هذه البلاطات.أظهرت النتائج العملية التي تم الحصول عليها من النتائج المختبرية أن عملية تقوية البلاطات الخرسانية باستخدام الياف الكاربون البوليمرية ادت الى زيادة في قيمة التحمل الاقصى للانحناء للبلاطات (Ultimate Loads) يصل مقدارها بين (8-64%) مقارنة بالبلاطات الخرسانية غير المقواة باستخدام الياف الكاربون البوليمرية . تم أستعمال التحليل اللاخطي بواسطة العناصر المحددة (Finite Elements) ثلاثية الأبعاد كوسيلة عددية للدراسة والتحري عن سلوك وتصرف هذه البلاطات باستخدام البرنامج (ANSYS الاصدار الثالث عشر) حيث تم في هذا البرنامج تمثيل الاجزاء الخرسانية باستخدام العناصر الطابوقية ذات الثمانية عقد (Solid 65) بينما تم استخدام العناصر القشرية ثلاثية الابعاد (3D Shell 41) لتمثيل شرائط الياف الكاربون البوليمرية وتم إفتراض وجود ربط تام بين شرائط الياف الكاربون البوليميرية و سطح تماس البلاطة الخرسانية.

INTRODUCTION

The structure may have to carry larger loads at a later date, or fulfill new standards. In extreme cases a structure will have to be repaired due to an accident. A further reason can be found that errors have been made during the design or construction phase resulting in need for strengthening the structure before usage. If any of these situations will arise; it needs to be determined whether it is more economic to strengthen the existing structure or replace it. In comparison to build a new structure, strengthening an existing one is often more economic[1].

Externally strengthening with advanced composite materials, namely, carbon fiber reinforced polymers (CFRP), represents the state-of-the-art in upgrading or rehabilitation techniques.

Depending on the member type, the objective of strengthening may be one or a combination of several of the following[2]:

(1) To increase axial, flexural or shear load capacities.
(2)To increase stiffness for reducing deflections under service and design.
(3) To increase the remaining fatigue life.
(4)To increase durability against environmental effects.

In spite of their promise, concern must be taken to existing materials. In some cases it can be difficult to reach the areas that need to be strengthened. Further, the existing documentation of the structure is often very poor and sometimes even wrong. Furthermore, when strengthening is going to be undertaken, all failure modes must be evaluated. For example, a flexure strengthening can lead to a shear failure instead of giving the desired carrying capacity. Also, it should be noted that not only the failure mode of the strengthened member is important. If a critical member in a structure is strengthened, another member can become the critical one and the whole structure must therefore be investigated.

FRP should not be used in the following situation [3].

- The condition of the substrate is unknown or largely deteriorated
- There is ongoing substantial corrosion of the mild-steel reinforcement
- There is no mild-steel reinforcement to provide ductile behavior

Types of Slabs and Their Applications

Slabs, in definition and the way of designing them, are structures that transmit loads normal to their plane. Concrete slabs are widely in use as floors not only in industrial and residential buildings but also as decks in bridges. They can be made in-situ as well as prefabricated and brought to construction site in full scale. For larger spans pre-stressed concrete is very often applied to increase capacity without extending slab thickness.

The biggest demand on concrete prefabricated slabs and shells appeared after World War (∏). Countries that suffered most needed a quick method to rebuild demolished residence buildings. That time many blocks of flats were built with prefabricated concrete shells and slabs, see Figure (1). Economic aspects and speed of construction were of the highest importance to provide citizens with flats as soon as possible. One-way slabs act structurally as wide beams with primary bending moments in one direction. Consequently in a one-way slab, the main reinforcement is placed in one direction to resist the loads, some secondary reinforcement is provided in the orthogonal direction to control cracking due to shrinkage and assist with load distribution. One-way slabs are applied in beam-and-girder system. The system contains a thin multispan slab carried by ribs, which are supported on frames, see Figure(2). Similar construction can be observed in heavy timber and steel structures. The advantage of such a system is that realistic moments can be calculated directly. Although a slab is designed as bent only in one direction it must be restrained also in the other, above a girder. Otherwise the upper side of the slab would crack in this region[4].

High Strength Concrete

It is a type of high performance concrete generally with a specified compressive strength of (40 MPa) or greater. High strength concrete is needed to, put concrete into service at much earlier age, build high-rise building reducing column size and increasing available space, build the superstructures of long-span bridges and to enhance durability of bridge decks, satisfy the specific need of special applications such as durability, modules of elasticity, and flexural strength. Some of these applications include dams, grandstand roofs, marine foundations, parking garages, and heavy duty industrial floors [6].

Details of Tested Slab:

Nine simply supported slabs(with high strength concrete), (SHS) where (S: slab,, H: high strength concrete , S: strengthened with CFRP) first slab (SH) was not strengthened with CFRP to serve as a reference slab(control slab), The remaining (8) slabs (SHS1, SHS2, SHS3, SHS4, SHS5, SHS6, SHS7, SHS8) study how the form in which the CFRP strips provided to the tension sides of the preloaded slabs effect to the flexural behavior of strengthening slabs. Two different space of CFRP were used(30&37.5mm) in slabs (SHS1, SHS2) in long direction , two different space of CFRP were used (100&120mm) in slabs (SHS3, SHS4) in short direction, the number of CFRP layers was also varied (one layer & two layers) keeping the CFRP to 37.5mm width in slabs (SHS5, SHS6), the slabs (SHS7, SHS8) were repaired with CFRP strips after loading the slabs to 67.4% and 80.2% of the ultimate load obtained for control slab SH. Table (1) shows the description of the tested slabs, and Figure (3) from (a) to (e) shows the control & strengthening scheme of the (SHS) group tested slabs.

Installation of CFRP Sheets

External strengthening of specimens by CFRP sheets was done according to the procedure recommended by the manufacturer which is described below:

- First of all, the CFRP sheets were cut into the required lengths. Surface preparation of the CFRP followed with cleaning to remove any dust or other contaminants prior to installation.
- The two-parts comp. A (white) and comp. B (black) of adhesive (Sikadur-330) were mixed respectively with an electric mixer (here electric low speed drill was used) and mixed in 4: l proportion, until the color was a uniform gray, the adhesive paste then was applied with a special tool to the concrete surface and the adhesive was also applied to the CFRP sheets.
- The strips were then placed on the concrete, epoxy to epoxy, and after the installation of strips , a ribbed roller was rolled in the direction of fibers to properly seat the sheets by exerting enough pressure so the epoxy was forced out on both sides of the strips.
- The adhesive was allowed to cure for at least 7 days before the slabs were tested. After completing the CFRP installation, two days before the testing date, all apparent concrete surface specimens were painted white to detect easily the crack propagation.

Figure (4) from (**a)** to (**e**) shows the strengthening scheme of the (SHS) group tested slabs.

Test Set-up and Instruments:

Torsee's Universal Testing machine with a capacity of 2000 kN was used to apply the load. The slab was loaded from of top at the mid-span. Load was applied in increments, with approximately fifteen load steps to failure. At each load increment, the total applied load on the slab, mid-span deflection, and crack width were measured. The cracks were plotted and marked. A test was terminated when the total load on the specimen started to drop off. The total time to failure in a test was approximately one hours. Figure(5), and Figure(6) shows the test setup.

Experimental Results:

1-Behavior of slab under loading and crack pattern:

The ultimate load and percentage increase in ultimate load with respect to reference slab are shown in Table (2).For the control slab, at early stages of loading, the deformations were initially within the elastic ranges (linear), then the applied load was increased until the first crack became visible which was observed in the maximum moment region under the point load. As the load was increased further, several flexural cracks initiated in the tension face at intervals throughout the slab, gradually increased in number, became wider and moved upwards reaching the compression face of the slab.

As the load was increased further, a loss of stiffness occurred and one mode of failure appeared which can be classified as flexural failure in tension by yielding of the steel reinforcement followed by crushing of concrete.

The strengthened slabs also showed similar behavior, but when the load reached yielding of steel, the CFRP strips contributed mainly in resisting the loads and increased the stiffness of the concrete slabs up to failure. The failure was usually recorded due to debonding of CFRP sheets from bottom face of slabs specimens which was very suddenly and the only indication of such failure was few popping sounds before debonding happened. In repaired slabs, the failure was similar to strengthened slabs, this because of the flexural strength mainly attributed to CFRP. The comparison of **SHS5** and **SHS6** with **SHS1** and **SHS2** it is interesting to note that when increasing the numbers of layers all this slabs fail at the same load levels. This means it is preferable to increase the area of strengthen by increasing the number of CFRP rather than increasing the thickness by increasing the number of layers.

2-Load Versus Mid-Span Deflection Results

Eight reinforced concrete slabs were strengthened by CFRP strips to examine the effect of strengthening patterns on their behavior and ultimate load capacity. Experimental investigation on the behavior of load versus mid-span deflection curves for these slabs is presented in the Figure (7). Obviously, it was noticed that the presence of CFRP sheets enhanced the behavior of strengthened and repaired slabs compared with the control slab by increasing the ultimate strength and reducing the ultimate central deflection.

3- Concrete Cracking

The slab control specimen SH was tested in order to have an unstrengthened slab to compare with CFRP strengthened and repaired slabs. The control slab behaved in an expected fashion under flexural loading. It was gradually loaded until the initiation of cracking. The appearance of flexural cracks was first at 12.5 kN within the maximum moment region under the point load. Flexural cracks formed and widespread as loading proceeded throughout the slab. At a load of 38 kN, the cracks reached the compression face of the slab. Failure of the control test specimen was by yielding of steel followed by crushing of the concrete at the compression zone at a load of 43 kN, as shown in Fig.(8.1)

For the first strengthened slabs specimens SHS1, which was strengthened with only fife parallel of CFRP strips installed on the tension bottom face of the reinforced high strength concrete slab, each strip has a length of 1700mm, width of 30mm, and thickness of 0.131mm. The cracks pattern of this slab specimen is shown in Figure (8.2). First crack occurred at a load of 17.3 kN, gradually the flexural cracks increased in intensity and widened. Cracks appeared at compression face at 48 kN. Failure was observed at load 57 kN by CFRP debonding (a separation at the interface between the substrate and the adherent material) due to propagation of diagonal flexural cracks at bottom face of the concrete slab. However, it was gained slightly increased in stiffness, restricted of cracks propagation and ultimate load from this pattern of strengthening.

For the second strengthened slabs specimens SHS2, which was strengthened with only six parallel of CFRP strips installed on the tension bottom face of the reinforced high strength concrete slab, each strip has a length of 1700mm, width of 30mm, and thickness of 0.131mm, failure was observed at load 62 kN by CFRP debonding due to propagation of diagonal flexural cracks at bottom face of the concrete slab. The cracks pattern of this slab specimen is shown in Figure (8.3)

For the third and fourth strengthened slabs specimens SHS3 and SHS4, which was strengthened with CFRP strips (the space of CFRP 100mm in short direction and 37.5mm in the long direction) for SHS3 and strengthened with CFRP strips (the space of CFRP 120mm in short direction and 37.5mm in the long direction) for SHS4. Failure was observed at load 67 kN for SHS3 and 74 for SHS4 by CFRP debonding due to propagation of diagonal flexural cracks at bottom face of the concrete slab. The cracks pattern of this slab specimen is shown in Figure (8.4). For the slab SHS5 strengthened with only fife parallel and two layer of CFRP strips and for the slab SHS6 strengthened with only six parallel and two layer of CFRP strips installed on the tension bottom face of the reinforced high strength concrete slab. Failure was observed at load 58.2 kN for SHS5 and 62.8 KN for SHS6 by CFRP debonding due to propagation of diagonal flexural cracks at bottom face of the concrete slab. It is interesting to note that when increasing the numbers of layers all this slabs fail at the same load levels

The two repaired slabs designated as SHS7 and SHS8, these slabs were similar to slab SHS2 in their strengthening patterns, the slabs were repaired by CFRP strips after loading to different percentages of ultimate load of the control slab SH. These load levels were (67.4%) and (80.2%) of ultimate load of the control slab SH for SHS7 and SHS8 respectively. The percentages increase in the ultimate loads for SHS7 and SHS8 were 25% and 22% with respect to the ultimate load of the control slab SH. Furthermore, Figures (9.1) to (9.2) showing the crack width developed and the CFRP effect on the reduction of crack width.

Numerical Applications

A nonlinear finite element analysis has been carried out to analyze the concrete slab , which are reinforced by CFRP strips and tested in this study. The analysis is performed by using ANSYS computer program (Version 13) which is running under system manager program (Windows seven) with applying the geometrical and material modeling .

In this section, verification is done in order to check the validity and accuracy of the finite element procedure. The ability of the constitutive finite element analysis method to simulate the behavior of this type of members is demonstrated through the analysis of the tested beams.

SHELL41 Element Description

SHELL41 is a 3-D element having membrane (in-plane) stiffness but no bending (out-of-plane) stiffness. It is intended for shell structures where bending of the elements is of secondary importance. The element has three degrees of freedom at each node: translations in the nodal x, y, and z directions. This element has variable thickness, stress stiffening, large deflection, and a cloth option [7], This element is used to simulate CFRP shear for all slabs.

SOLD65 Element Description

SOLID65 is used for the 3-D modeling of solids with or without reinforcing bars (rebar). The solid is capable of cracking in tension and crushing in compression. In concrete applications, for example, the solid capability of the element may be used to model the concrete, while the rebar capability is available for modeling reinforcement behavior. Other cases for which the element is also applicable would be reinforced composites (such as fiberglass), and geological materials (such as rock). The element is defined by eight nodes having three degrees of freedom at each node: translations of the nodes in x, y, and z-directions. Up to three different rebar specifications may be defined. The most important aspect of this element is the treatment of nonlinear material properties. The concrete is capable of cracking (in three orthogonal directions), crushing, plastic deformation, and creep. The rebars are capable of tension and compression, but not shear. They are also capable of plastic deformation and creep. This 8-node brick element is used, in this study, to simulate the behavior of concrete (i.e. plain concrete). The element is defined by eight nodes and by the isotropic material properties [7].

Numerical Result

1-Loads at Failure

In general, the predicted ultimate load obtained by ANSYS-13 gives agreement with experimental result. In most of the slabs, the finite element ultimate load overestimated the experimental results by (3% - 12%). Table (3) shows the compression between experimental and numerical results.

There are several factors that may cause the higher stiffness in the finite element models. Microcracks produced by drying shrinkage and handling are presented in the concrete to some degrees. These would reduce the stiffness of the actual slabs, while the finite element models do not include microcracks. Perfect bond between the concrete and steel reinforcing are assumed in the finite element analyses, but the assumption would not be true for the actual slabs. As bond slip occurs, the composite action between the concrete and steel reinforcing is lost.

2- Crack Patterns

In ANSYS computer program, the cracking or crushing types of fracture in concrete elements appear as circles at locations of these cracking or crushing, the shape of each crack and crush in concrete element is summarized as follows

1- Cracking is shown with a circle outline in the plane of the crack,
2- Crushing is shown with an octahedron outline.
3- If the crack has opened and then closed, the circle outline will have an X designation through it.

A cracking sign appears when a principal tensile stress exceeds the ultimate tensile strength of the concrete and appears perpendicular to the direction of the principal stress. The cracking sign appears perpendicular to the direction of the principal stress.

To obtain good results from the Solid65 element, the use of a rectangular mesh is recommended. Therefore, the mesh was set up such that square or rectangular elements were created Figure (10). The volume sweep command was used to mesh the steel plate and support. This properly sets the width and length of elements in the plates to be consistent with the elements and nodes in the concrete portions of the model. Figure (10.1) to (10.2) shows the evolution of crack patterns in ANSYS program of load level (0.9 Pu) for control slab SH. On the other hand, the variations in strain and stress in the X and Z directions for control slab (SH) are shown in Figures (11).

Conclusions

Based on the overall results obtained from the experimental work and the finite element analysis for the externally strengthened or repaired reinforced concrete height strengthened slabs by CFRP strips, the following conclusions can be drawn as follows:

1. The externally strengthened reinforced high strength concrete one-way slabs with bonded CFRP sheets show a significant increase in ultimate loads and the capacity of the slabs, this increase is about (8-64%) compared with the unstrengthened (control).

2. The external CFRP strips attached to the tension faces of reinforced concrete slabs increase the stiffness of the slabs at all stages of loading, and consequently reduces the deflection at corresponding loads.

3. The use of CFRP sheets as external strengthening has a significant effect on crack pattern of the reinforced concrete one-way slabs by delaying the crack appearance and reducing the crack width, the increase in cracking loads is about (8-60%) compared with the unstrengthened (control) slab.

4. In all slab specimens strengthened with external CFRP sheets, the cracks pattern for flexural failure as similar. The appearance of flexural cracks was first within the maximum moment region under the central concentrated load, the cracks formed and widespread as loading proceeded throughout the slab move to the top face of the slab. The crack width continues to increase till the CFRP failed (Debonding of CFRP).

5. The use of CFRP sheets as external strengthening in two direction in one- way slab has a significant effect on crack pattern of the reinforced concrete one-way slabs by delaying the crack appearance and reducing the crack width, the increase in cracking loads is about (17-19%) compared with the strengthened slab in one direction.

6. The percentage of increase in the load carrying capacity of the repaired slab is almost similar to that of the corresponding strengthened slabs.

Acknowledgments:

This study was performed in the structures Laboratory at the University of Basrah, Iraq. An expression of gratitude is presented to the staff of Structural materials laboratory and the library for their assistance in preparing the study.

Table (1) shows the description of the tested slabs.

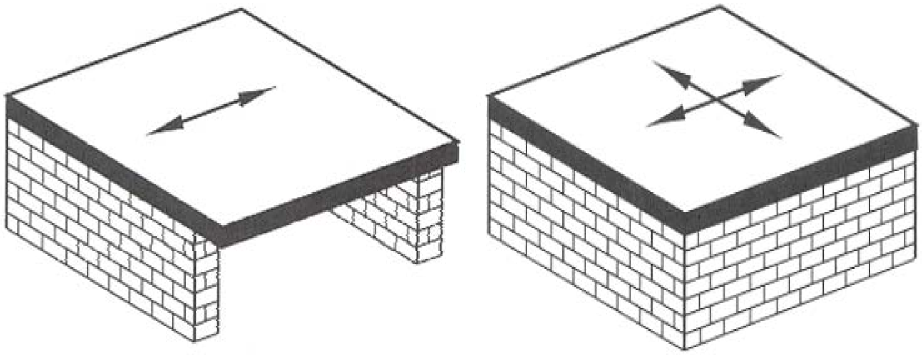
Slab No.	Details of Slab
SH	Reference slab (control slab) without strengthening
SHS1	Slab strengthened with CFRP strips (the space of CFRP 37.5mm in the long direction)
SHS2	Slab strengthened with CFRP strips (the space of CFRP 30mm in the long direction)
SHS3	Slab strengthened with CFRP strips (the space of CFRP 100mm in short direction and 37.5mm in the long direction)
SHS4	Slab strengthened with CFRP strips (the space of CFRP 120mm in short direction and 37.5mm in the long direction)
SHS5	Slab strengthened with two layer CFRP (the space of CFRP 37.5mm in the long direction)
SHS6	Slab strengthened with two layer CFRP (the space of CFRP 30mm in the long direction)
SHS7	Slab retrofitting with CFRP strips, (the space of CFRP 30mm in the long direction)loading to 67.4% of the ultimate load
SHS8	Slab retrofitting with CFRP strips, (the space of CFRP 30mm in the long direction) loading to 80.2% of the ultimate load

Table (2) First cracking loads of the tested slabs

Specimen	First cracking load (kN)	Increase in cracking load(%)
SH	12.5	N/A
SHS1	16.5	32
SHS2	17.3	38
SHS3	19	52
SHS4	22.2	77
SHS5	18.1	44
SHS6	16.8	34
SHS7	15.6	24
SHS8	14.6	16

Table (4) Comparison between Experimental and Numerical Ultimate Load of the Analyzed Slabs

Beam Designation	Numerical FailureLoads(KN)	Experimental FailureLoads(KN)	P(Num.)/ P(Exp.)
SHS1	60.99	57.0	1.07
SHS2	66.96	62.0	1.08
SHS3	74.37	67.0	1.11
SHS4	76.96	74.0	1.04
SHS5	64.68	62.8	1.03
SHS6	58.68	52.4	1.12
SHS7	63.3	53.7	1.17
SHS8	62.2	52.2	1.19



One-way slab *Two-way slab*

Figure (1) One-way and two-way slab [3]

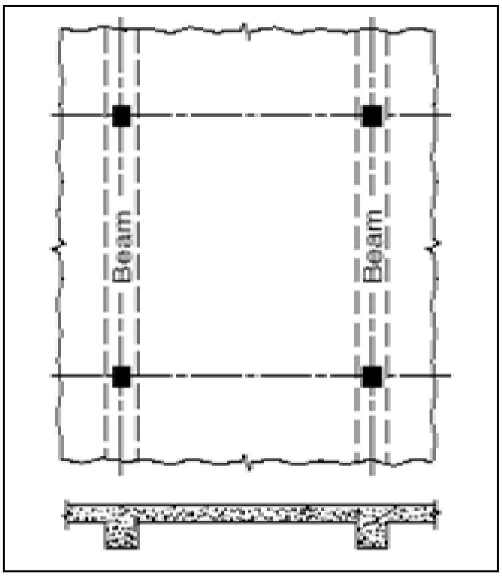


Figure (2) one-way slab supported with beams

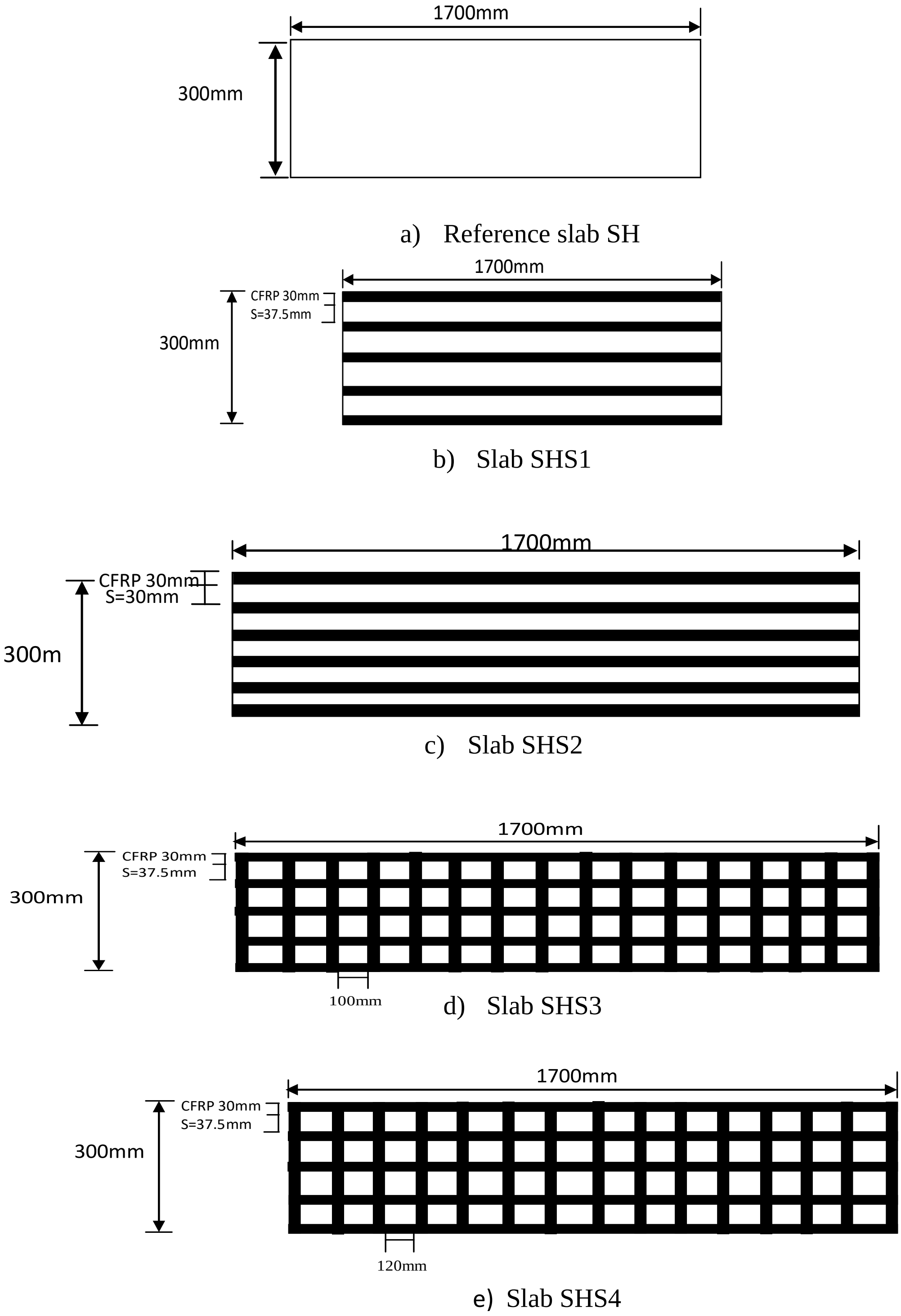


Figure (3) control & strengthening scheme of the (SHS) group tested slabs.

a) Slab SHS1

b) Slab SHS2

c) Slab SHS3

Figure (4) strengthening scheme of SHS group

Figure (5) Test Setup

Figure.(6) Test Sample

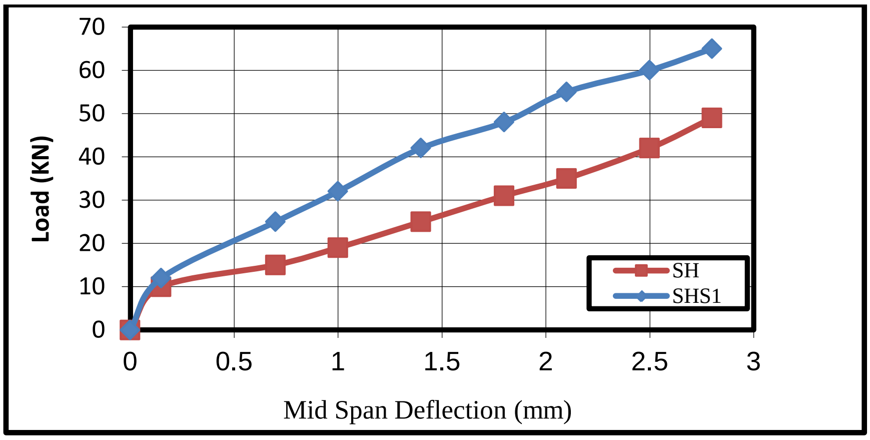


Figure (7) Load versus mid-span deflection

Figure (8.1) Cracks pattern after failure for slab SHC

Figure (8.2) Cracks pattern after failure for slab SHS1

Figure(8.3) Cracks pattern after failure for slab SHS2

Figure (8.4) Cracks pattern after failure for slab SHS3

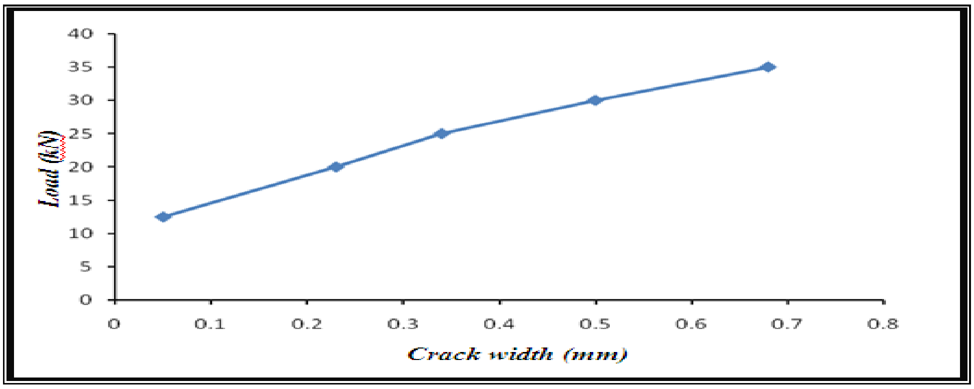


Figure (9.1) Crack width versus applied load for slab SH

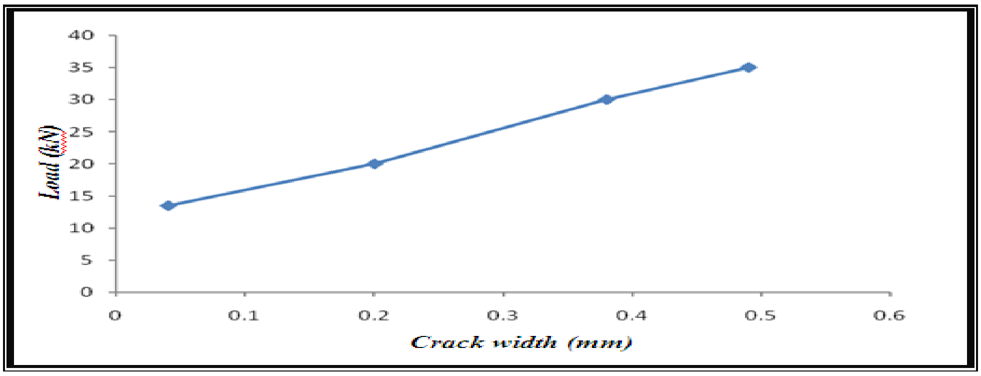


Figure (9.2) Crack width versus applied load for slab SHS1

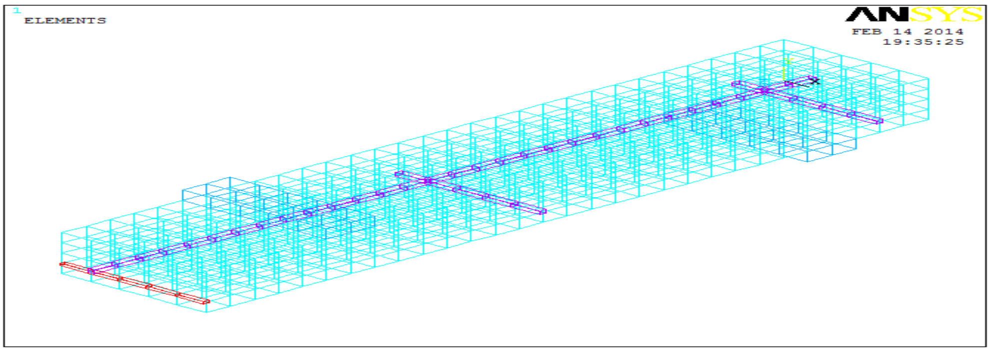


Figure (10) Element Mesh and Materials Attributes.

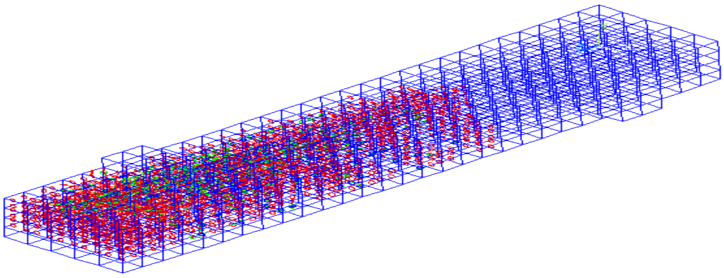


Figure: (11.1): Numerical crack patterns of SH

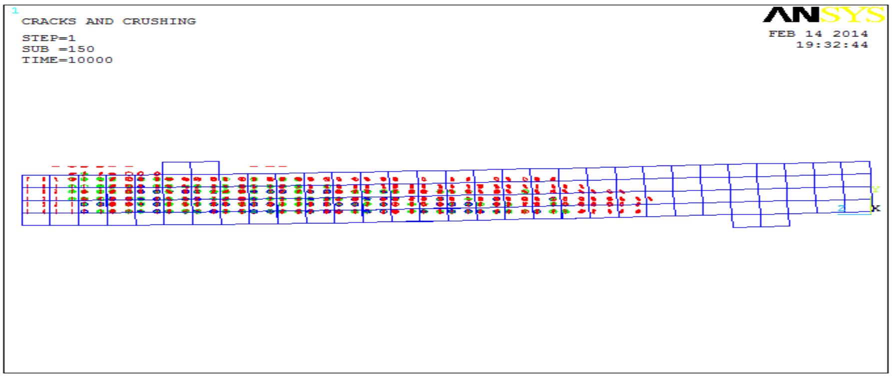
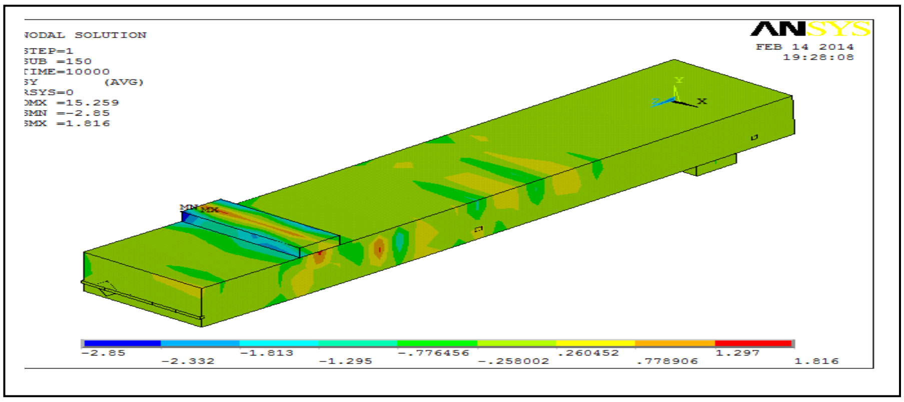


Figure: (11.2): Numerical crack patterns of SH



Figure(12)the variations in strain and stress in the X and Z directions for control slab (HS)

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