



Finite Element Modeling of Reinforced Concrete Slabs Strengthened in Flexural with NSM-CFRP

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ABSTRACT:

This study is devoted to investigate the behavior and performance of R.C. slabs strengthened with near surface mounted (NSM-CFRP). A system of computer program (ANSYS V.12.1) is used for analysis at this study. The ordinary reinforced concrete is modeled by 8-node isoparametric brick elements, while the steel reinforcing bars is modeled as axial members (bar elements) connecting opposite nodes in the brick elements with a full interaction assumption. The NSM CFRP strips were modeled by shell element. The effect of some selected parameters (thickness and shape) is studied. It is found that the ultimate load increased efficiently with increasing the thickness of NSM (87% & 123% for slabs S1 & S2 respectively). Concrete strength of R.C. slabs tested is (f_c' 18.85). The maximum increment in terms of the slab load carrying capacity is limited by the concrete crushing.

Keywords: Reinforced concrete slab, Flexural strengthening, NSM (near surface mounted CFRP reinforcement).

الخلاصة:

أن الغرض من هذا البحث هو التحري عن تصرف وأداء السقوف الخرسانية المسلحة والمقواة بألياف الكربون البوليميرية. استخدم برنامج الحاسبة التحليلي (ANSYS V.12.1) في إجراء هذه الدراسة المستخدمة في هذا البحث. مثلت الخرسانة باستخدام العناصر الطابوقية ثمانية العقدة. إما قضبان التسليح الاعتيادية فقد تم تمثيلها كعناصر محورية تربط نقاط متقابلة في العنصر الطابوقي مع فرض وجود تلاصق تام بين هذه النقاط اما الصفائح الكربونية المركبة فقد مثلت كعناصر رقائقية. نظمت دراسة نظريه لاختبار تأثير بعض المتغيرات مثل (سمك وشكل الالياف). وقد تم التوصل إلى إن الحمل الأقصى يزداد مع زيادة سمك الالياف (٨٧% و ١٢٣% للبلطات S1 و S2 على التوالي). بينت النتائج ان قابلية التحمل للبلطات ذات مقاومة الانضغاط الواطنة (مقاومة انضغاط ١٨,٨٥MPa) تتحدد بتهشم الخرسانة (concrete crushing).

Notation:

E_s	Modulus of Elasticity of Steel
f'_c	Uniaxial Compressive Strength of Concrete (Cylinder Test)
f_y	Yield strength of steel bar.
ε	Strain , σ Stress
GFRP	Glass Fiber Reinforced Polymer
CFRP	Carbon Fiber Reinforced Plastic
ε_{y0}	Strain of steel at yielding

INTRODUCTION:

The use of near surface mounted (NSM) is currently emerging as a new technology for increasing flexural and shears strengths of RC members.

(Gemert, 2000) [1], repaired the roof slab of a former school building in Leuven, Belgium, that was transformed into a city library with a considerable increase of load as a consequence. The floor slabs had to be strengthened to increase the bearing capacity from 3 kN/m² to 6 kN/m². An extensive material investigation was done to determine the material properties and the condition of the construction. Six concrete cores (Ø113 mm) were drilled to determine the concrete compressive

strength, resulting in a characteristic value of 22.1 N/mm^2 . A more recent and less investigated method for shear strengthening of RC members is the use of near-surface mounted (NSM) FRP reinforcement, usually in the form of round bars or of rectangular bars with large width to thickness ratio (herein briefly indicated as strips). In the NSM method, the reinforcement is embedded in grooves cut onto the surface of the member to be strengthened and filled with an appropriate binding agent such as epoxy paste or cement grout.

(Toong, 2002) [2], presented the behavior of reinforced concrete one-way spanning slabs strengthened by carbon fiber reinforced plastic plates (CFRP) to increase the flexural capacity with particular emphasis on the cracking behavior at working load levels. A total of nine slab specimens were cast to investigate three parameters: steel ratio, pre-loading, and length of CFRP plate. Six specimens were utilized to study the effects of pre-loading before the CFRP plates were attached. The final specimen had a full length CFRP plate to compare with the efficiency of taking the plates beyond the supports. Preload of 60% and 80% of the ultimate capacity of the member was applied. All the CFRP strengthened specimens exhibited large increase in load carrying capacity ranging from 60% to 140% with no significant difference in the load carrying capacity for slabs with and without preload. CFRP strengthened members which were preloaded and pre-cracked resulted in wider cracks compared to the members which were not preloaded. Significant improvement in the crack behavior can be achieved with the addition of CFRP plates at the crack widths.

(Fu-Ming et al., 2004) [3], presented a reasonable numerical model for reinforced concrete structures strengthened by FRP. Proper constitutive models were introduced to simulate the nonlinear behaviors of reinforced concrete and FRP. The finite element program **ABAQUS** was used to perform the nonlinear failure analysis of the discussed problems. The validity of proposed material models was verified with experimental data and some strengthening schemes were discussed in detail for engineering applications. It has been shown that the use of fiber reinforced plastics can significantly increase the stiffness as well as the ultimate strengths of reinforced concrete slabs. In addition, the nonlinearity of FRP in-plane shear stress-strain relation does not influence the behavior of such composite slabs, because of the small failure shear strain of the composite plates. By considering the proper constitutive models, the authors present a rational numerical model to analyze the reinforced concrete structures strengthened by FRP. In verification, the behavior of both RC slab and retrofitted slab were predicted accurately against the experimental data. If longitudinal directions of the FRP coincide with the yielding lines of RC slabs, the ultimate load of the slab may not increase too much. The best strengthening scheme can be achieved if the longitudinal directions of the FRP and the directions of the maximum bending stress were in parallel.

(Limam et al., 2007) [4], tested two 7 cm*130 cm*170 cm R.C. two-way slabs with carbon fiber reinforced plastic (CFRP) strips bonded to the tensile face. Results of the experimental study indicate that externally bonded CFRP plates can efficiently used to strengthen two-way R.C. slabs. Results were compared to those of a solid slab without opening and a slab with an unstrengthen opening. The CFRP system proved to be effective in enhancing the load-carrying capacity and stiffness of RC slabs with an opening, provided that premature failure due to CFRP debonding is excluded.

In a study conducted by (Paulo et al., 2007) [5], his focus was on evaluating the flexural behavior of near surface mounted (NSM) system for strengthens reinforced concrete slab. In the experimental program, a total of five R.C. slab tests were conducted. One R.C. slab specimen was used as control specimens without composites and remaining four R.C. specimens were strengthened with NSM.

(Abbasi et al., 2008) [6], modeled RC slabs strengthened with CFRP plates and sheets using ANSYS computer program (version 9.0, 2004) under Microsoft Windows XP (service pack 1, 2002) based on a smeared cracking approach. Perfect bond was assumed between CFRP sheets and concrete interface. This method, however, neglects the premature debonding failure of slabs; with the assumption slip does not take place at the CFRP plate/concrete interface, can be used in additional studies to develop design rules for strengthening reinforced concrete bridge members by using FRP.

Finite Element Representation of Reinforced Concrete beam with NSM CFRP Reinforcement:

The element types for this model are shown in Table (1).The SOLID65 element is used to model the concrete. This element has eight nodes with a three degrees of freedom at each node translation in the nodal x, y and z directions. This element is capable of plastic deformation, cracking in three orthogonal directions and crushing. Link 8 was used to represent the flexural reinforcement and NSM CFRP reinforcement, while Shell41 represents the CFRP strips, SOLID45 element are used to model the plate loading and supporting, (ANSYS-V.12.1 2009) [7].

Table (1): Element types for working model.

Material type	ANSYS element
Concrete	SOLID 65
Flexural Reinforcement	LINK 8
NSM-CFRP	SHELL 41
Plate loading	SOLID 45

Concrete Brick Element:

The 8-node isoperimetric linear element (SOLID65) shown in figure (1), which is used in this study. Each of the eight corner nodes has three degrees of freedom u , v , and w in the X , Y and Z directions respectively.

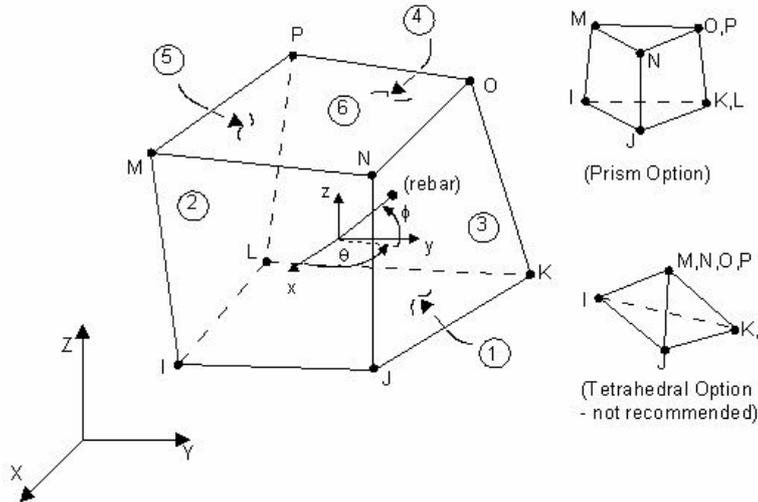


Figure (1): Brick element with 8 nodes (ANSYS V. 12.1) [7].

Finite Element Idealization of Reinforcement:

In this study the discrete model is used to represent steel reinforcement and NSM CFRP. The three-dimensional two-node bar element (link8) is a uniaxial tension-compression element with three degrees of freedom at each node (nodal translation in x , y and z) directions. The axial normal stress is assumed to be uniform over the entire element. The element x -axis is oriented along the length of the element from node (1) towards node (2), figure (2).

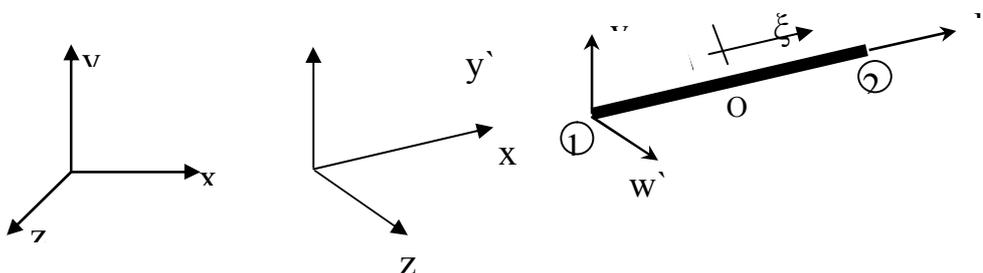


Figure (2): Bar element ANSYS V. 12.1 [7].

As the element is capable of carrying axial loads only, then the strain-displacement relationship is as follows:

$$\varepsilon = \varepsilon'_x = \frac{\partial u'}{\partial x'} \quad (1)$$

SHELL41 Element (Membrane shell)

A shell 41 element is used to model CFRP strips. SHELL 41 is a 3-D element shown in figure (3), 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. The element can have variable thickness, stress stiffening and large deflection.

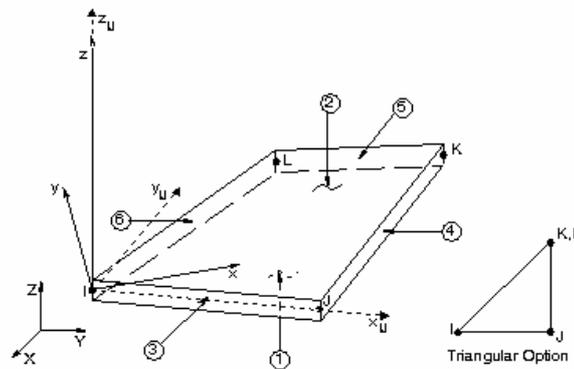


Figure (3): SHELL 41 geometry ANSYS V. 12.1 [7].

Concrete Modeling:

➤ **Stress-Strain Relationship:**

The Solid 65 element requires linear isotropic and multilinear isotropic material properties to properly model concrete as shown in figure (4), the modulus of elasticity is calculated by equation of (ACI- code 2008) [8].

$$E_c = 4730\sqrt{f'_c} \quad (2)$$

The ANSYS program requires the uniaxial stress-strain relationship for concrete in compression in figure (4).

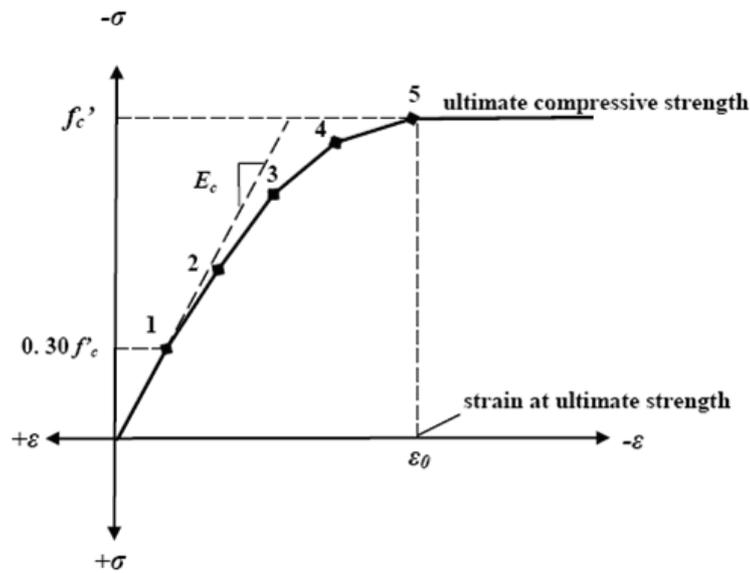


Figure (4): Simplified compressive uniaxial stress-strain curve for concrete (Kachlakev et al., 2001) [9].

Modeling of Reinforcement:

Typical stress-strain curves for reinforcing steel bars used in concrete construction are obtained from coupon tests of bars loaded monotonically in tension. For all practical purposes steel exhibits the same stress-strain curve in compression as in tension. The steel stress-strain relation exhibits an initial linear elastic portion, a yield plateau, a strain-hardening range in which stress again increases with strain and finally a range in which the stress drops off until fracture occurs. The extent of the yield plateau is a function of the tensile strength of steel, (Cervenka et al., 1990) [10].

Where, $E_w = 0.1E_s$

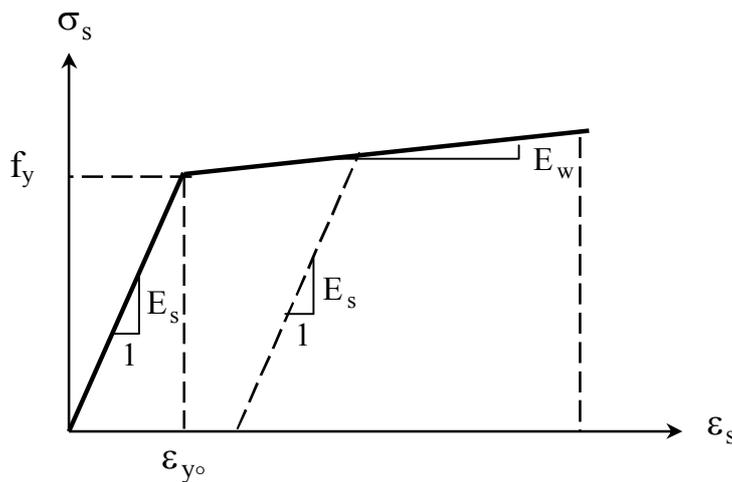


Figure (5): Typical stress-strain curve for steel bar, (Mattock, 1981) [11].

Modeling of FRP Reinforcement:

The stress-strain behavior of FRP reinforcement is linear-elastic to failure. As a result, the FRP reinforcement is classified as brittle versus steel which is ductile. As a comparison, the yield strain of grade 60 steel is approximately 0.002, which is about one-tenth of the ultimate strain available in the FRP reinforcement. Thus, if a masonry structure is reinforcement with some type of FRP, the structure will continue to gain strength until there is either a bond failure between the FRP and the masonry, rupture of the FRP reinforcement, or crushing of the masonry. Figure (6), shows the typical constitutive relationships for common materials.

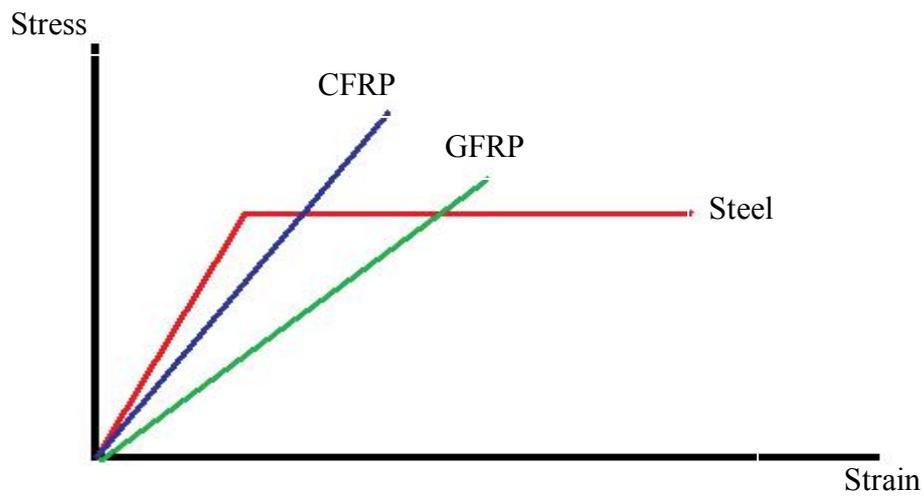


Figure (6): Behavior of Typical Materials, (John, 2009) [12].

Verification Study:

This finite element analysis (FEA) calibration study includes modeling a concrete slab with the dimension and properties corresponding to solid slab tested by (Paulo et al., 2007) [5]. The dimensions of the full-size slabs were (80*300*2000) mm. The span between two line supports (1800) mm. longitudinal reinforcements and NSM are modeled throughout the slab. The goal of the comparison of the FE model and the slab from (Paulo et al., 2007) [5] is to ensure that the elements, material properties and convergence criteria are adequate to model the response of the member and make sure that the simulation process is correct.

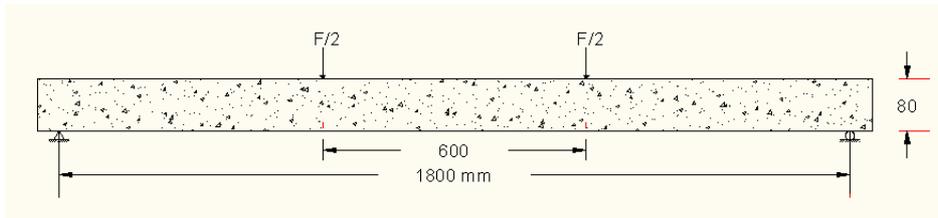
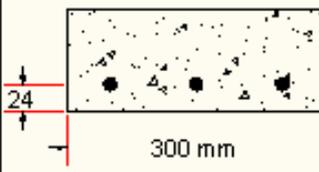
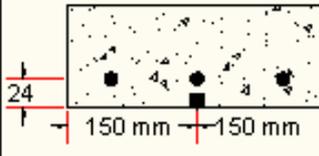
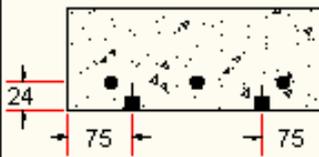


Figure (7): Test setup configuration (dimensions in mm) by (Paulo et al., 2007) [5].

Table 2: Details of the specimen's cross sections

slab specimen	cross section	No. of steel bar	No. of laminates
S0		3Ø8 mm	0
S1		3Ø8 mm	1
S2		3Ø8 mm	2

All dimensions in mm

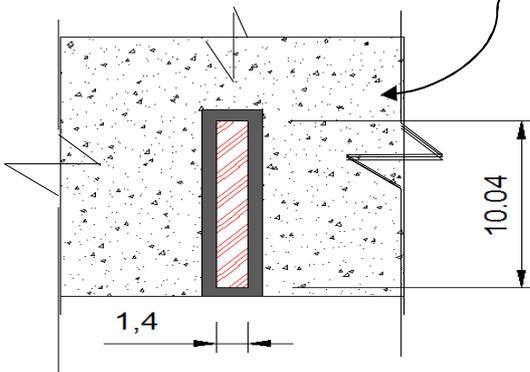


Table 3: Summary of the characteristics of the steel reinforcement and NSM and concrete [5].

Steel reinforcement	NSM
Φ_s (diameter of bar) = 8 mm E_s (modulus of elasticity) = 200.80 GPa σ_{sy} (yield strength of steel) = 438.20 MPa	t (width) = 1.40 mm h (extension) = 10.04 mm E (modulus of elasticity) = 161.41 GPa σ_{fu} (yield strength) = 1776.35 MPa

Loading and Boundary conditions.

Boundary conditions are needed to be applied at nodes in the supports to ensure that the model acts the same way as the experimental slab. The supports were modeled in a way that the roller and hinged supports were created. The load was represented in the finite element model by (10, 12 and 18) equivalent nodal forces of the slab (S0, S1 and S2), as shown in figure (8).

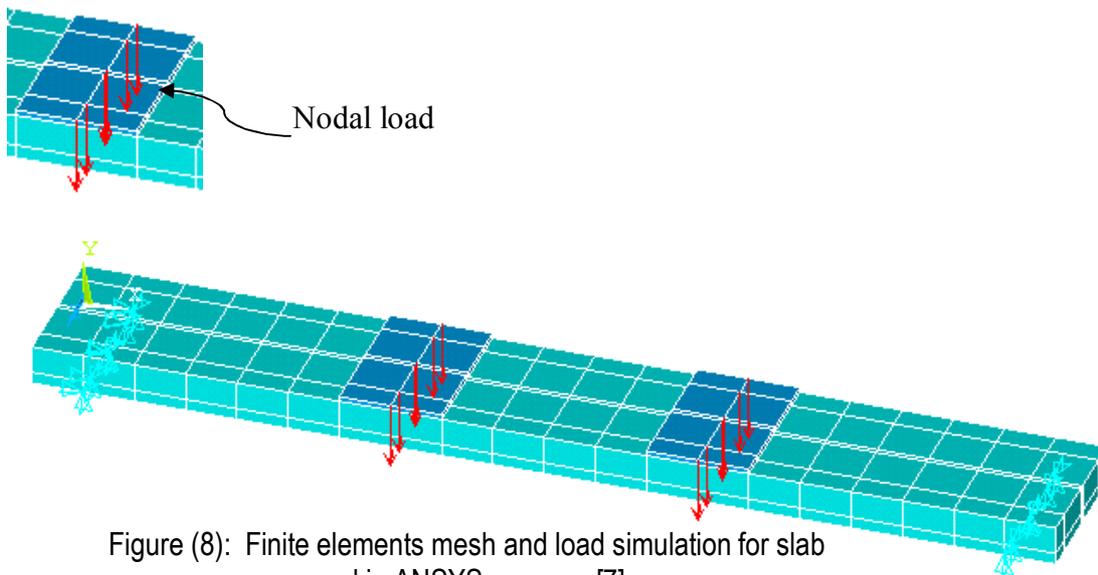


Figure (8): Finite elements mesh and load simulation for slab used in ANSYS program [7].

Results of the finite element model:

Figures (9, 10, 11) shows the relationship between deflection at slab mid-span and load, for both the experimental tests and the numerical analyses (assuming perfect bond). The analytical ultimate load (10.75, 13.5, 20.4 kN) is detected quite well compared with that experimentally observed (11, 14, 21 kN) for slab (S0, S1, S2) respectively. It's obvious from the tested slab results, that the finite element model is stiffer than the experimental one and this may due to two causes, the first one because of the assumption of the perfect bond between the slab and CFRP which means no slipping between them, while the second reason is due to that the micro cracks produced by drying shrinkage and handling are present in the concrete to some degree which are not simulated in the finite element model.

Figures.(9, 10, 11) shows that the failure load obtained from the numerical solution for all slabs is slightly smaller than the experimental load. The explanation of this behavior is that the final loads for the finite element model are the last applied load step before the solution diverges due to numerous cracks and large deflections.

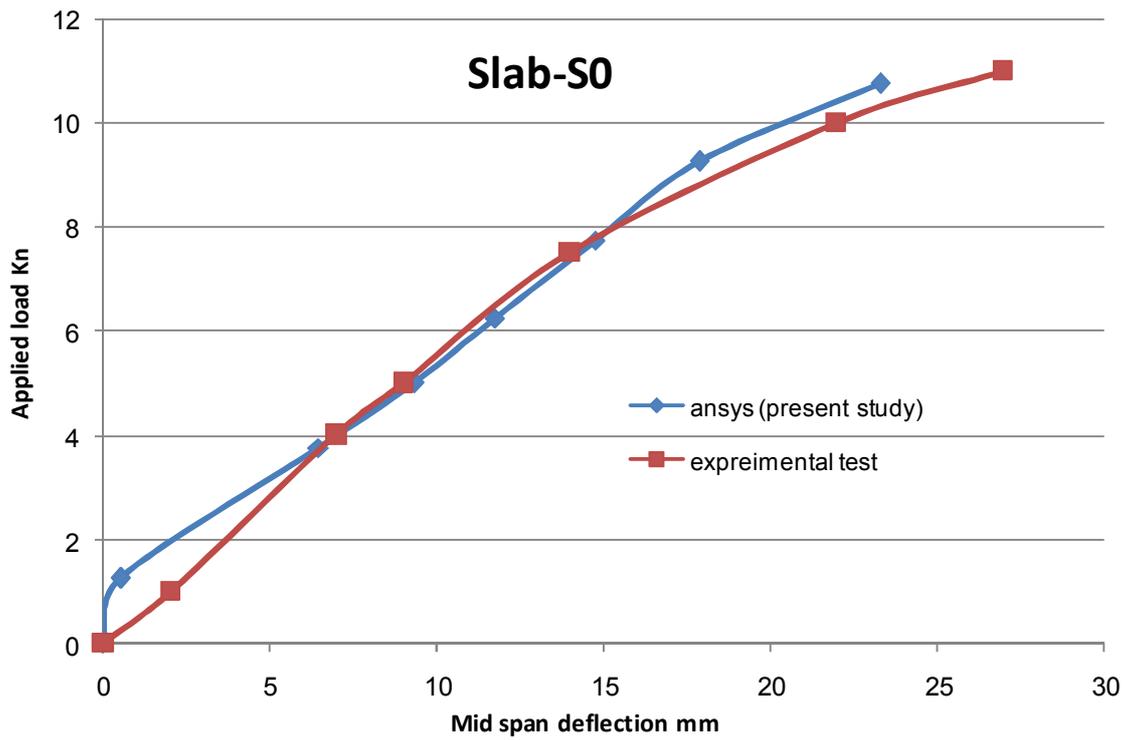


Figure (9): Load-deflection curve for slab (S0)

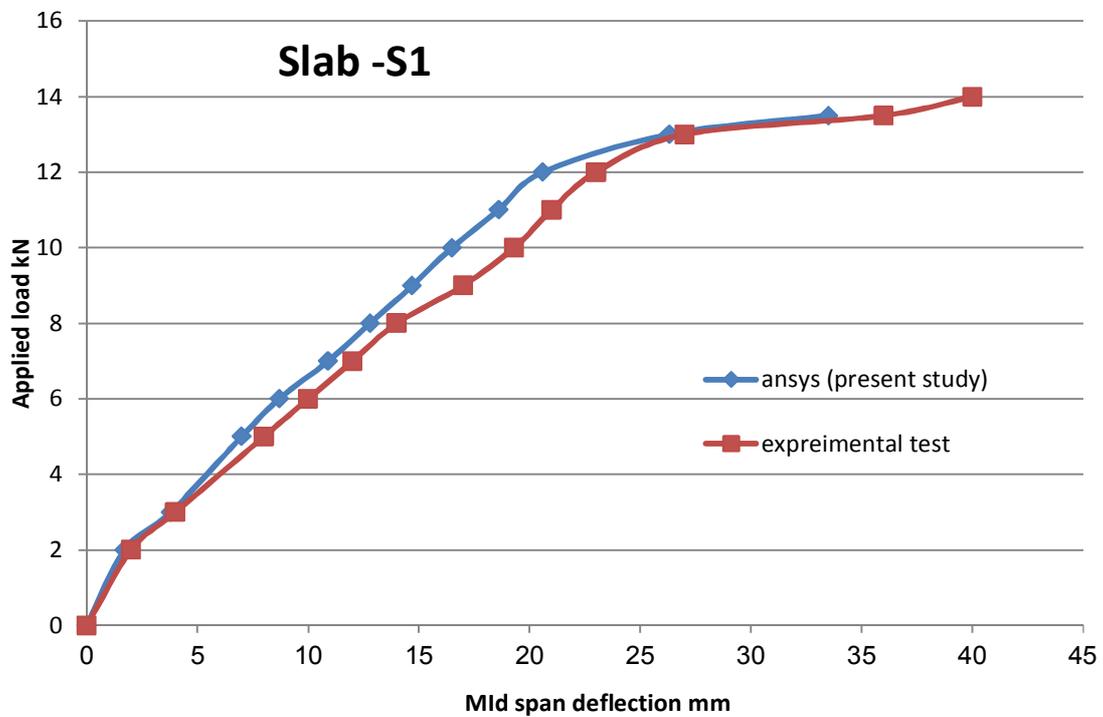


Figure (10): Load-deflection curve for slab (S1)

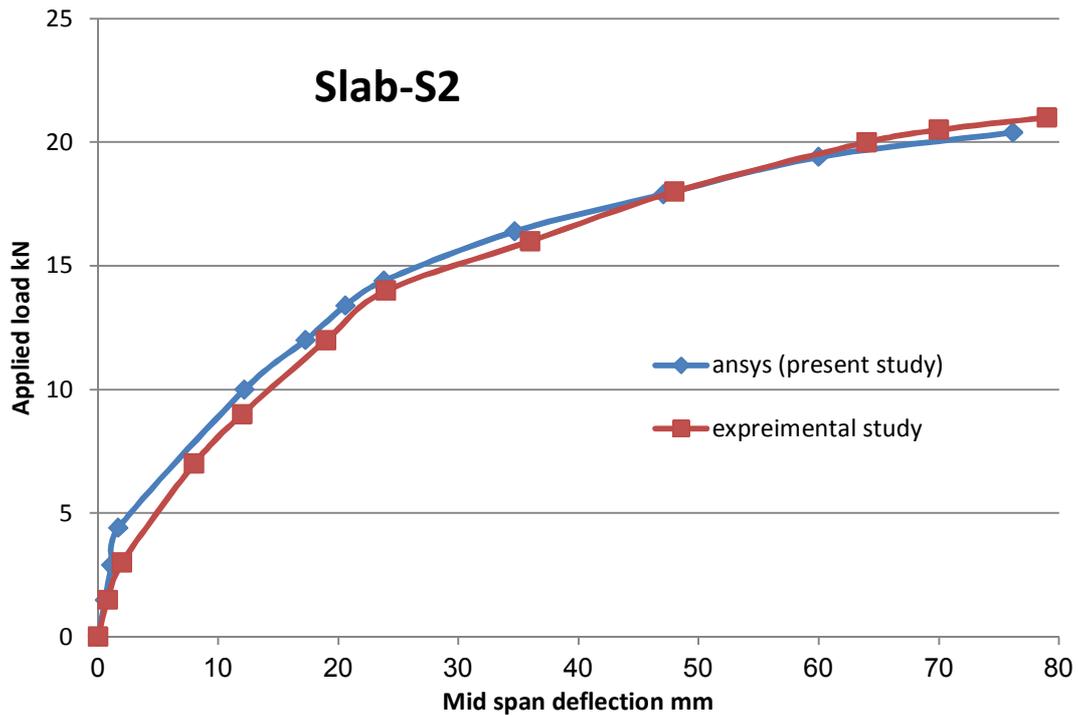


Figure (11): Load-deflection curve for slab (S2)

Generally, the deflection of the slabs strengthened with NSM was lower than the deflection of the corresponding control slab.

Analysis and results of NSM-CFRP concrete slab.

1- Thickness effect of NSM-CFRP.

Different five thickness of near surface mounted were used in the present study through the stiffening the slabs (S1) and (S2) to study the effect on the behavior of the slabs.

The thickness values were used in the present study are (t , $1.5t$, $2t$, $2.5t$, $3t$) where (t) is equal to 1.4mm.

Figures (12&13) show the effect of NSM-CFRP thickness on the behavior of slabs tested. It's shown from the figures above NSM-CFRP enhanced the behavior of all slabs tested and for all different thickness of NSM-CFRP. The degree of enhancement in the strength is related with the increase of this thickness, so the overall stiffness of R.C slabs are enhanced. The more effective increment in the ultimate load are found for the slab (S1) more than the slab (S2) as shown in the figures (12&13). The effect of thickness increase on the behavior of the two slabs are significant until the value of ($2.5t$), while above this thickness the enhancement in the ultimate load of the two

slabs are limited to crushing of concrete at compression zone. The ultimate load increments are (87%) & (123%) for S1 & S2 respectively due to the presence of NSM-CFRP.

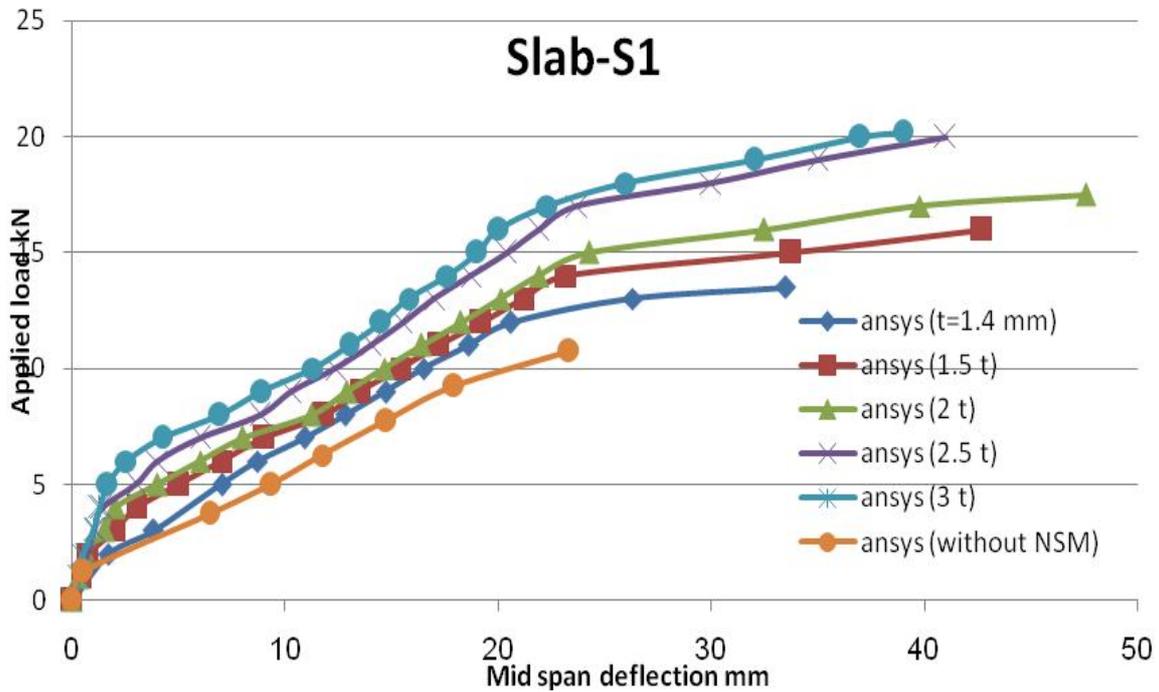


Figure (12): Load-deflection curve for slab (S1)

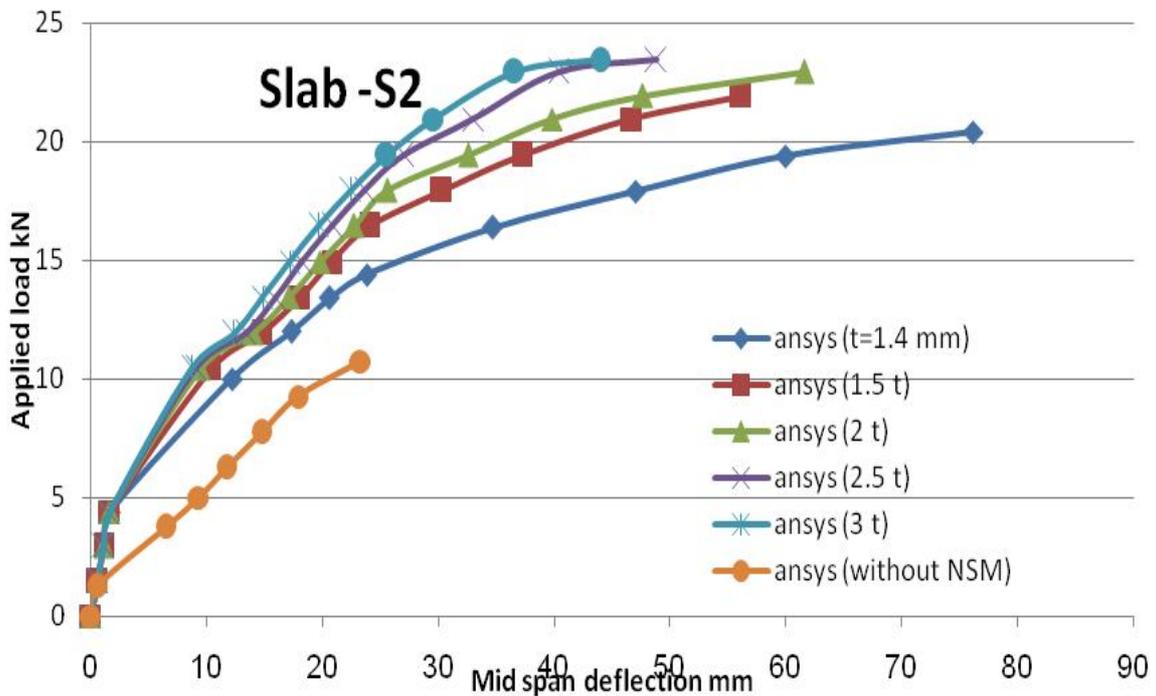


Figure (13): Load-deflection curve for slab (S2)

2- Effect the shape of NSM-CFRP.

To study the effect of the shape of the NSM-CFRP on the behavior of the strengthened concrete slab. The following cases are considered:

1. The original case has NSM of (t=1.4 mm) width and (h=10.04 mm) up extension beyond the length of the slab.
2. The second case has NSM of (4.23 mm diameter (bar)).
3. The third case has NSM of (t=2.8 mm) width and (h=5.02 mm) depth.

In prescribed the two cases (2&3), the area of NSM is kept the same as in the original one (case1). Figures (14&15) show the effect of the shape of the NSM on load-deflection behavior of strengthened slab. It can be noted that the bar shape is more efficient and give significant results behavior than the other bars due the homogenous stress distribution at the interlock position between the slab and NSM-CFRP bar. The max. increasing in ultimate load was (40%) for (S1) and (106%) for (S2).

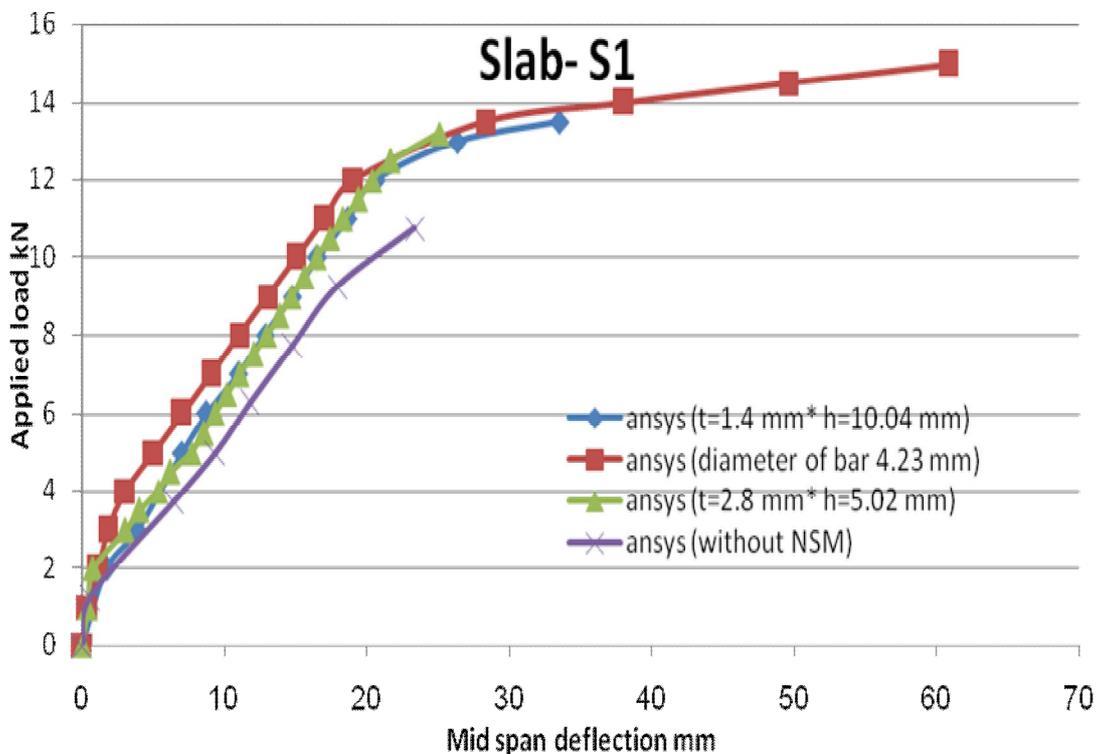


Figure (14): Load-deflection curve for slab (S1)

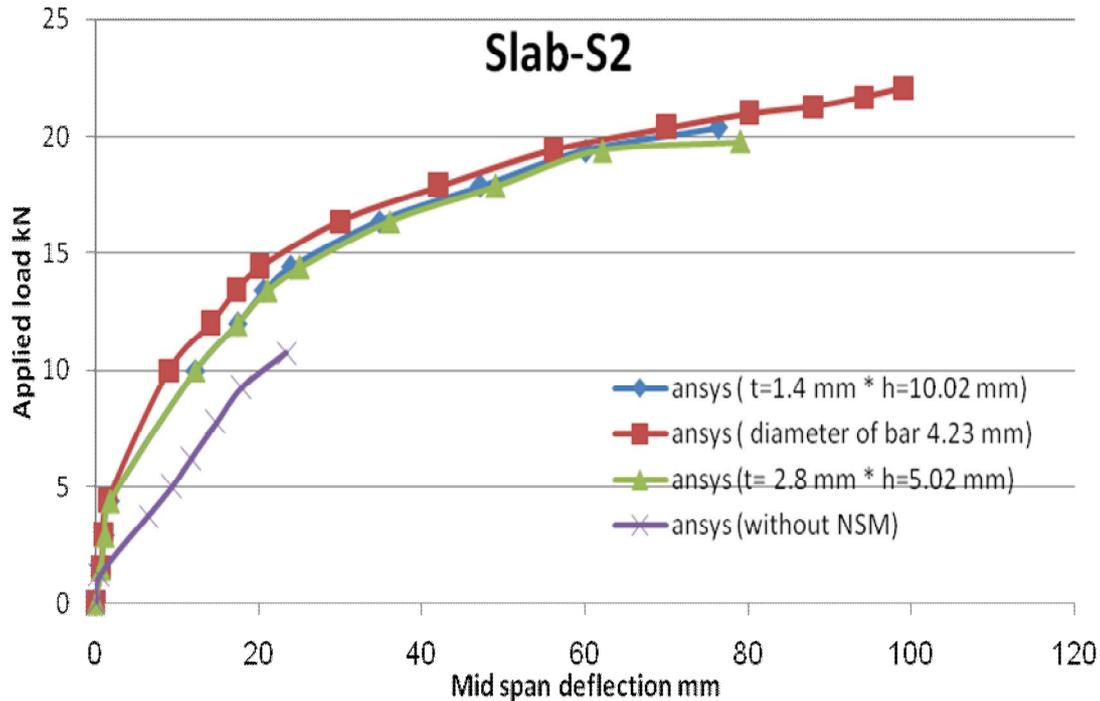


Figure (15): Load-deflection curve for slab (S2)

Conclusions:-

- 1-The three-dimensional nonlinear finite element model presented in this study by using the computer program (ANSYS V.12.1) is able to simulate the behavior of reinforced concrete slabs strengthened in flexural with NSM-CFRP. The numerical results were in good agreement with experimental load-deflection curves throughout the entire range of behavior.
- 2- The test results confirm that the strengthening technique of NSM-CFRP system is applicable and can increase the flexural capacity of RC slabs.
- 3- The ultimate load increase to (87% & 123%) for (S1 & S2) respectively with increasing the thickness of NSM-CFRP. But the maximum increment in terms of the slab load carrying capacity is limited by the compressive strength of concrete due to the crushing of concrete at compression zone.
- 4- It was found that the variation of NSM-CFRP shape has a real effect on the predicted and ultimate load of slab concrete members. It can be noted that bar shape in the slab is better than the other two shapes used in this study with a max. increase in ultimate load of (40% & 106%) for the slabs S1 and S2 respectively.

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