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Numerical Investigation of Reinforced Concrete One-way R.C. Slabs Reinforced with Hybrid HFRP Bars

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Abstract—**This paper presents a nonlinear finite element model to investigate the flexure behavior of concrete slabs reinforced with hybrid HFRP reinforcement bars. Different types of hybrid bars, locally produced by hybridizing with steel wires, are used in studying the behavior of concrete slabs. The study is conducted using the nonlinear finite element program ''ANSYS 19". Nonlinear material models for the components of the concrete slab are used in the three dimensional finite element models. The outcomes obtained from the finite element analysis are correlated with experimental results. A broad parametric study is conducted to explore the effect of replacing steel reinforcement by different types of HFRP bars. The study showed that the contribution of hybrid rebars HFRP in concrete slabs improved slabs ductility and eliminated the unfavorable brittle failure of the concrete member.**

***Keywords*— Hybrid FRP, locally produced, Concrete Slabs Flexural behaviour, Parametric study, ANSYS, Finite element analysis.**

I. INTRODUCTION

Numerous studies on fiber reinforced polymer composite bars (*i.e.*, FRP Bars), as a substitute for reinforcing bars, have been conducted to solve the corrosion problem of steel in reinforced concrete structures [1],[2].

However, they are not popular as a construction material due to: 1) higher price than the conventional steel reinforced bars; 2) brittleness characteristics different from fiber behaviors of reinforced bars; 3) low elastic modulus [3] - [4].

Material properties including brittleness and low elastic modulus can be improved by combining them with materials that have higher elastic modulus. Nanni et al. [5] developed a hybrid rod consisting of FRP braided skin made up of glass, aramid or vinylon fiber and a steel core .Based on the hybrid rebars properties and previous research (Hwang, J.-H.et al.(2014), Park, C. et al. (2016), Dong-Woo Seo et al. (2016), Minkwan Ju, et al. (2017) and Yingwu, Z., Yaowei, Z.et al.(2018), Jinkyo F. Choo et al. (2018)) [6]-[11], a unique type of hybrid FRP rebar is proposed and developed by the first author, along with others, to achieve the required level of modulus of elasticity and ductility requirements, at reasonable cost.

This study focused on simply supported HFRP-reinforced concrete slabs based on existing study M. Abo Elyazed et al. [12]. The locally produced HFRP Bars, hybridizing by GFRP/steel wires (FRP Hybrid Bars), are mainly considered and their performance is tested as a function of the proportion of core steel wires. In detail, the effects of the proportion of GFRPs and steel wires as well as hybrid methods are compared and analyzed through tensile tests to ensure the validity of developed models.

Through these processes, the development of optimized FRP Hybrid Bars is in attempt to finally apply to marine and waterfront structures to replace the steel rebars.

The principle aim of this study is to build up a nonlinear finite element model to investigate the flexure behavior of concrete slabs reinforced by three different types of hybrid HFRP bars. The finite element commercial program ANSYS (19) is utilized in the analysis. Nonlinear material properties of the slab components are used. The results obtained from the model are confirmed against the test results conducted by previous experimental tests [12]. An extensive parametric study is conducted to investigate the effect of the concrete compressive strength, main flexural reinforcement ratio and size effect.

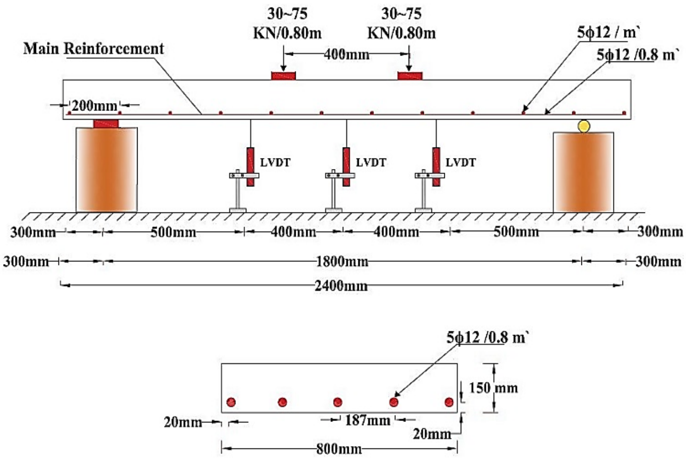

Fig. 1 Dimensions and details of verified experimental slabs [12].

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A. General

In order to accurately simulate and actual flexure behavior of the concerned slab, all its components; concrete slab, reinforcement bars; have to be modeled properly. Meanwhile, choosing the element types and mesh size are important as well in building the model to provide accurate results with reasonable computational time.

Recent experimental tests on concrete slab reinforced with GFRP, steel and HFRP [12] are used to verify the developed finite element model.

The overall length of tested slabs [12] is 2400 mm. The slabs are simply supported with a rectangular cross-section of 800 mm width and 150 mm depth. A four-point static loading technique is utilized to examine the simply supported slab with a span of 1800 mm, as detailed in Fig. 1. The dimensions and material properties of the verified specimens are summarized in Table 1.

B. Element type modeling

Three dimensional non-linear finite element analysis is conducted to simulate the flexural behavior of concrete slabs reinforced with the new developed HFRP bars. The commercially available finite element analysis software package, ANSYS (ANSYS release 19.0), is used in this process. The load-deflection curve is considered the key aspect in studying the hybrid slabs behavior as it involves response parameters including slab ultimate loads, first cracking load, and maximum deflection. Therefore, correlating the load-deflection relationships of the analytical results with that of the experimental ones is considered an effective mean to verify the proposed model. The load condition and boundary condition for conventional and hybrid slabs are same and it is shown in the Fig. 2 .

A linear isotropic material model is used to represent the concrete. This material is known as quasi brittle material and has different behaviour in compression and tension. In this present study Solid 65 element is used to model the concrete. This element has eight nodes having three degrees of freedom at each node, i.e. translations in the nodal X, Y and Z directions respectively and the element is capable of cracking and crushing in three orthogonal directions .

A multi-linear isotropic material model is used to represent steel reinforcement and a multi-linear orthotropic material model is used to represent hybrid reinforcement. A link 180 element is employed to model the reinforcement. It is two node elements and each node has three degrees of freedom.

Translations are in the nodal X, Y and Z directions. This element is also capable of undergoing plastic deformation. The stress strain curve for reinforcement is obtained from bars tested in tension. The properties of hybrid bars are obtained from the experimental results.

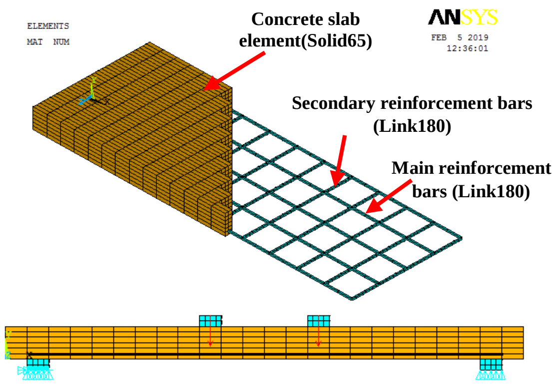

Fig. 2 A typical figure of the 3-D FE mesh

C. Material modeling

The material properties of the pre-tested specimens are detailed in Table 1. For all slab models, the Poisson's ratio of concrete is taken 0.2 and the ultimate strain of the concrete at failure is taken as 0.0035. A multilinear isotropic stress-strain relation is used for modeling concrete material in compression. This relationship consists of two portions. The first portion is

an ascending curve represented by the numerical expressions (Desayi and Krishnam 1964); Eqs. (1) and (2), [14] along with (Gere and Timoshenko 1997) Eq. (3) [15]. The curve starts at zero stress and zero strain toward a value of 0.3fc, calculated from Eq. (3), Fig.3. The remaining points of the ascending curve are obtained from Eq. (1). The strain at ultimate stress of concrete is calculated via Eq. (2). A bilinear relationship is used to represent the stress-strain curve of the steel and hybrid HFRP reinforcement while a linear elastic behavior is used for the GFRP rebars.

The Poisson's ratio is assumed to be 0.3 for steel reinforcement, 0.25 for HFRP and 0.2 for GFRP. For loading plates, the stress-strain relation is considered linear. Table 2 shows the material properties of the experimental database for different materials used.

Table **1** Designation of verified slabs [12]

Slab Notation	Slabs dimensions		Effective Span, L (mm)	Reinforcement Rebar type		Tensile Strength (MPa)	Elastic Modulus (MPa)	Ultimate Strain	Concrete properties F_{cu} MPa
	Width, b (mm)	Depth, t (mm)		Type of bar	Bottom reinforcements				
S-S	800	150	1800	Steel	5Ø12/0.8m'	650.44	200	0.032	40
S-G (REF)	800	150	1800	GFRP	5Ø12/0.8m'	575.22	41	0.0157	39
S-H-A	800	150	1800	HFRP (A)	5Ø12/0.8m'	299.12	42.5	0.011	35
S-H-B	800	150	1800	HFRP (B)	5Ø12/0.8m'	330.97	46.53	0.012	36
S-H-C	800	150	1800	HFRP (C)	5Ø12/0.8m'	442.48	51	0.01	37

$$f = \frac{E_c \varepsilon}{\left[1 + \left(\frac{\varepsilon}{\varepsilon_0}\right)^2\right]} \quad (1)$$

$$\varepsilon_0 = \frac{2 f_c}{E_c} \quad (2)$$

$$E_c = \frac{f}{\varepsilon} \quad (3)$$

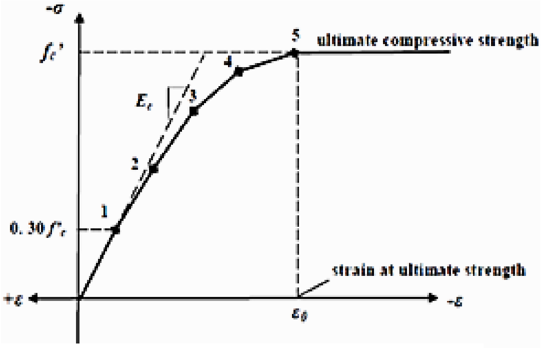

Fig. 3 Simplified compressive uniaxial stress-strain curve for concrete

Table 2 Material properties of the experimental database

(1) Concrete	
Concrete strength (f_c)	40,33,32,30 and 38 MPa ,respectively.
Young modulus of elasticity (E_c)	24149 to 26587 GPa
Poison's ratio (γ)	0.2
(2) Steel	
Maximum tensile strength (f_t)	600 MPa
Young modulus of elasticity (E_t)	2e5
Poison's ratio (γ)	0.3
(3) GFRP	
Young modulus of elasticity (E_t)	55.3 GPa
Poison's ratio (γ)	0.2
(4) HFRP-A	
Maximum tensile strength (f_t)	300 MPa
Young modulus of elasticity (E_t)	42.5 GPa
Poison's ratio (γ)	0.25
(5) HFRP-B	
Maximum tensile strength (f_t)	331 MPa
Young modulus of elasticity (E_t)	46 GPa
Poison's ratio (γ)	0.25
(6) HFRP-C	
Maximum tensile strength (f_t)	575.22 MPa
Young modulus of elasticity (E_t)	54 GPa
Poison's ratio (γ)	0.25

D. Boundary conditions and load application

Following the testing procedures conducted in the experimental data base [12], simply supported boundary conditions are applied at the position of edge support, as shown in Fig. 2. The load is applied in small increments to avoid non-convergence problems. This is achieved with the aid of the load steps and sub-steps. Cracking and crushing of concrete elements are monitored during the loading steps. The load is applied until failure in all slabs.

E. Verification of finite element model

To validate the finite element model, a comparison is held among available pre-tested slabs and the finite element results. For all the slabs, flexural cracks appeared when the concrete's tensile strength is reached and, consequently, the cracking moment is reached in the pure bending zone. Cracks are observed at the tension zone within and near the constant moment region.

A comparison of the analytical with experimental ultimate loads of the test specimens are given in details elsewhere [12]. The ratio of the analytical to experimental ultimate load for the slabs ranged between 0.94 and 1.12, with a mean value of 1.088 and a C.O.V of 8.49%. Implicitly, the analysis reflected the significance of test parameters investigated on the load-carrying capacity. Also, the ratio of the analytical to experimental ultimate deflection for the slabs ranged between 0.64 and 0.91, for which the standard deviation is 0.167 mm and the coefficient of variation is 11.3%.

The results of the proposed 3-D nonlinear finite element model correlated with the experimental results fairly well and the finite element model proposed is capable of capturing the flexural behavior of slabs reinforced with HFRP bars.

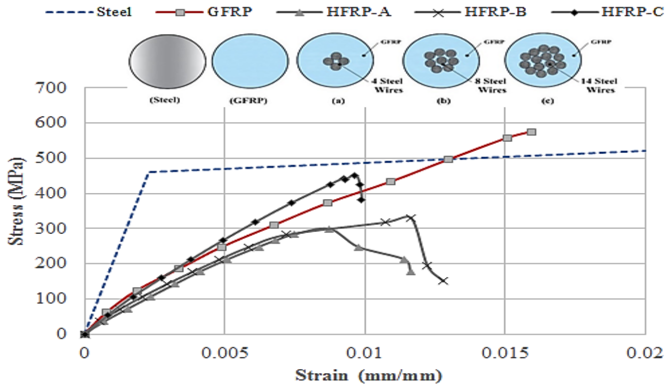

Fig. 4 Typical stress-strain curves for Steel , GFRP and HFRP

III. PARAMETRIC STUDY

A parametric study through the parametric study database, displayed in Table 3 is analyzed using ANSYS software. A total of seven concrete slabs are analyzed in the current parametric study. The verified model is used in analyzing slabs in closed in the parametric study database, examining the following variables:

a) Concrete compressive strength ;
b) Main flexural reinforcement ratio;
C) Size effect.

Dimensions, loading pattern and material properties followed exactly the experimental work. The studied slabs are divided into three groups with different hybrid reinforcement, as detailed in Table 3.

The main objective of the parametric study is to investigate different parameter affecting the flexural behavior of HFRP reinforced concrete sections. In particular, the influence of different parameters on the load capacity, deflection response

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at failure of HFRP reinforced sections has been developed using the non-linear FE software, ANSYS, as presented in the next section.

A.Parametric Study Database Analysis and Results

The FE predicted failure loads, mid-span deflections, and the maximum HFRP longitudinal strains for the parametric study database are displayed in Table 3 and Fig. 5 to Fig.7.

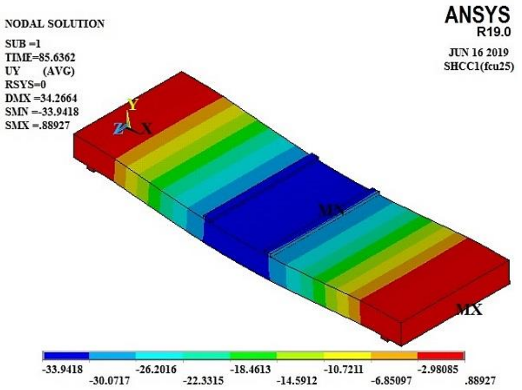

Fig.5 Deflected profile of Hybrid one way $SHCC_1$ slab

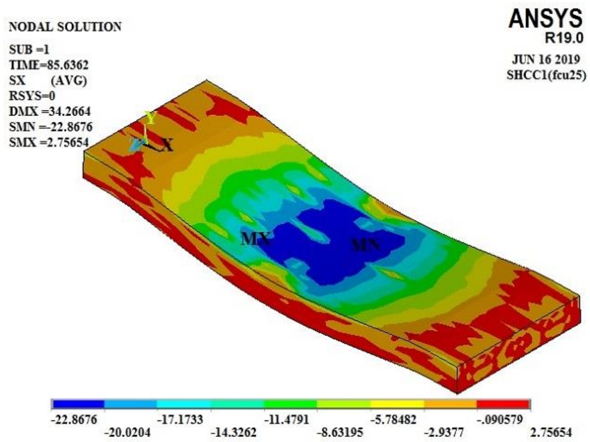

Fig.6 Stress contours profile of Hybrid $SHCC_1$ slab

Table 3 Parametric Study Database

Slab series	Model	Parametric study	Slab section t x b (mm²)	Main Reinforcement No.	Main Reinforcement Type	F_{cu} MPa	P_u (ANSYS) kN/m'	Δ mm	Reinforcement F_{fu} MPa	Reinforcement ε_{fu}	Failure mode
Control slabs Ref[12]	SS	Reference	150 X 800	5Ø12	**Steel**	38	120	36.9	490.2	0.00614	Flexural-Tension
	SG			5Ø12	**GFRP**	38	88.5	25.4	446.6	0.0081	Combined shear and flexure
	SHC			5Ø12	**HFRP-C**	38	80	36.3	480.2	0.009	Combined shear and flexure
I	$SHCC_1$	Concrete Compressive Strength, F_{cu} (MPa)	150 X 800	5Ø12	**HFRP-C**	25	85.6	33.7	453.31	0.0084	Flexural-Tension
	$SHCC_2$			5Ø12		30	90.8	38	461.51	0.0085	Flexural-Tension
	$SHCC_3$			5Ø12		35	96.68	44.5	472.61	0.0087	Flexural-Tension
II	$SHC\rho_1$	Different Reinforcement Ratio	150 X 800	**5Ø10**		38	76.8	32.8	490.8	0.018	Flexural-Tension
	$SHC\rho_2$			7Ø10		38	81	41	410.52	0.016	Flexural-Tension
III	$SHCS_1$	Size Effect	**125**x800	5Ø12		38	76.5	48.7	470.2	0.0145	Flexural-Tension
	$SHCS_2$		**100x800**	5Ø12		38	45.25	34.4	364.78	0.00676	Concrete crushing

C: Concrete Compressive Strength, ρ: Reinforcement Ratio and **S**: Size Effect

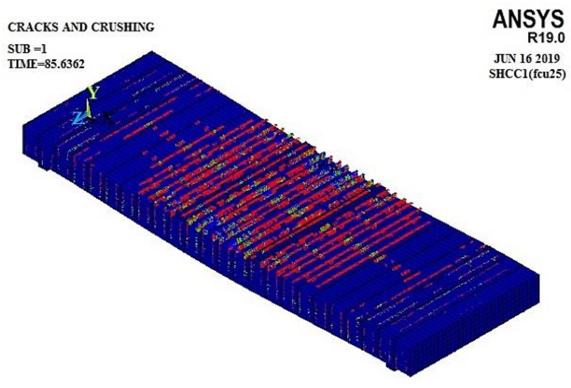

Fig. 7 Cracks propagation for Specimen $SHCC_1$

B.Analysis Results of Parametric Study

The parametric study for slab type (C) is carried out by assuming the volume of concrete for all modelling slabs are the same volume except SHA slab model. The main purpose of this study is to investigate the effect of using a new devolved HFRP on the stiffness and ultimate load capacity for reinforced concrete members.

1) The influence of increasing the Concrete Compressive Strength, Fcu:

The case study under consideration includes the influence of increasing the concrete compressive strength on the flexural characteristics of the hybrid slab models at failure, such as the load capacity and the deflection capacity values. The study is conducted on four proposed models group I ($SHCC_1$, $SHCC_2$ and $SHCC_3$) respectively. Table 3 exposes the effect of varying concrete compressive strength on the flexural characteristics (Load capacity and maximum deflection) of the proposed model.

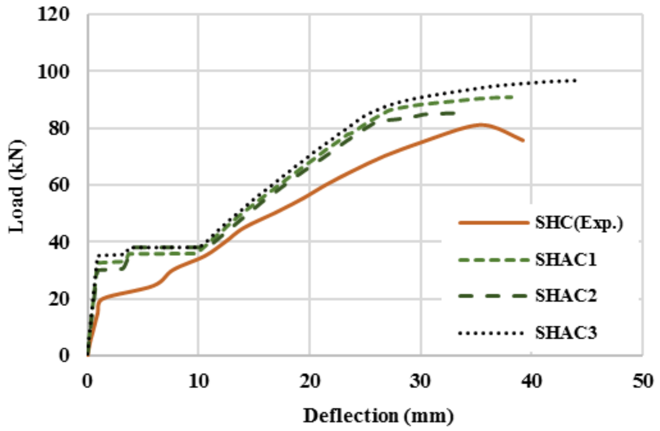

Fig.8 Load-deflection curves for group I

Table 3 compares the results obtained for the ultimate load values, taking into consideration the alteration of concrete compressive strength on the flexural characteristics of modelling slabs. It has to be noted that in case of using F_{cu} = 25 MPa ($SHCC_3$), the proposed ultimate load values increase by an amount of 12.94% in the case of model $SHCC_1$, and by an amount of 6.47% in the case of model $SHCC_2$. One can observe that the increases the concrete strength capacity by an average amount 16.67-40% for all experienced slabs models make convergence of the hybrid model to the conventional steel slab. This means that the existence of the high concrete strength for hybrid slabs has a major effect on the strength capacity values.

The three models of (Group I) are investigated in order to investigate the effect of concrete compressive strength. Fig.8 presents a comparison of the results of the ultimate deflection values. It has to be noted that there is slight difference in deflection between the studied slabs models, in case of $SHCC_2$ slab, the proposed values of the maximum deflection increase by an average amount of 2.98-20.6% for all hybrid slabs models compared with the conventional steel slab.

2) The influence of different reinforcement ratio

In this part, the effect of changing reinforcement ratio of hybrid slabs on the characteristics of the flexural failure stage for the hybrid slabs is investigated. Two hybrid slabs with two different reinforcement ratio 0.327% and 0.458% are proposed and applied to the model SHCρ_1 and SHCρ_2, respectively. Fig.9 investigate the effect of varying reinforcement ratio of hybrid bars on the failure characteristics of the proposed model.

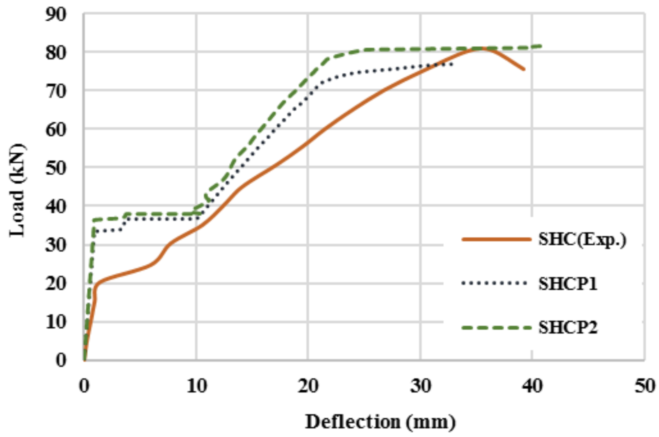

Fig.9 Load deflection curves for group II

Fig. 9 presents a comparison of the results of the ultimate load capacity. This study is applied to the model type C (SHCρ_1 and SHCρ_2) with the same concrete dimension as indicated previously. It has to be noted that the case of the hybrid slab model (SHCρ_2) which had reinforcement ratio 0.458% had slight increase in ultimate load value by 1.25% compared to the experimental model SHC, whereas the case of the hybrid slab model (SHCρ_1) with reinforcement ratio 0.327% had the maximum one 4% decrease.

Table 3 compares the results obtained for the maximum deflection values, taking into consideration the same models and the proposed reinforcement ratio indicated above. It has to be observed that there is slight decrease of the maximum value. The maximum deflection values for hybrid slab model SHCρ_1 decrease by significant value of approximately 9.64% and increased by 22.58% for SHCρ_2 model compared with the experimental model SHC.

3) The influence of Size Effect

The influence of size effect for slabs by varying thickness of the slabs (Group III) on the characteristics of the failure stage for the hybrid slabs is studied herein. Two different slab thicknesses of values 100 mm and 125 mm are proposed and executed to the model SHC, as a case study. Fig. 10 explicates the effect of size effect on the fracture characteristics of the proposed model.

Table 3 presents a comparison of the results of the ultimate load values. This study is applied to the model (Type-C) with the same concrete compressive strength values as mentioned above. It has to be noted that the case of the hybrid slab model with slab thickness of 100 mm had the minimum ultimate load value, whereas the case of the slab thickness of 150 mm had the maximum one. The decrease in the ultimate load for two consecutive hybrid slab thicknesses (e.g. 100

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mm and 125 mm) reached remarkable value of approximately 4.375-43.4% compared with hybrid slab SHC.

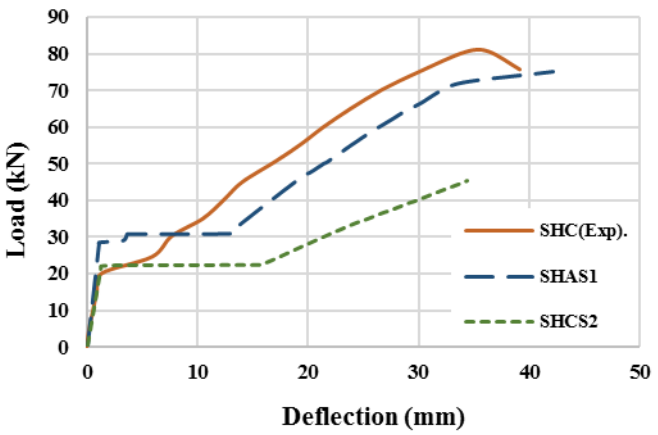

Fig.12 Load deflection curves for group III

Table 3 compares the results obtained for the maximum deflection values, taking into consideration the same model and the proposed hybrid slab thicknesses as presented above. It has to be observed that the case of the hybrid slabs model including lower slab thickness of 125 mm has the maximum value of the maximum deflection, whereas the case of the lower slab thickness of 100 mm has the minimum one. The decrease in the maximum deflection values for two consecutive slab thicknesses (e.g. 100 mm and 125 mm) reached a slightly remarkable average value of approximately 5.23% compared with hybrid slab SHC.

IV. CONCLUSIONS

This study investigated the flexural behavior of concrete slabs reinforced with new developed locally produced hybrid bar (HFRP) with a core of steel wires. The combination of GFRP crust and steel core for the manufacture of reinforcing hybrid bars appears to be a developed technology for use in concrete structure applications.

- The GFRP/steel hybrid developed system is beneficial in terms of improving the serviceability, ductility, and energy absorption of the concrete structure member, But The load capacity of the hybrid slabs decreased by as much as 23.07 to 47.8% compared to the slab with normal GFRP bars, owing to the type of the hybrid bar.
- The tensile test exposed that the hybridization of the GFRP and steel wires in core presented an increasing in modulus of elasticity and low ultimate strength as compared to the GFRP bar. The bilinear behavior of the HFRP (Glass/steel wires) bar specified good ductility as compared to the brittle failure of the normal GFRP bar at the ultimate state without any sign of fracture. Hybrid bars (Type C) specimen showed the better tensile strength closer to normal GFRP and the ductility is higher than any other types of GFRP reinforcing products.
- A numerical proposed model based on the finite element theory can be used to examine the geometrical and mechanical characteristics in new developed hybrid slabs, resulting in a good agreement when comparing to available full-scale test data.
- Based on the finite element numerical study and the experimentally available results, the comparison of the load capacity values obtained by the proposed and experimental models leads to a good agreeable between them. An average increase in the proposed load capacity values of approximately 11.15% compared to the experimentally available data is concluded for all proposed models. However, a closer performance of the validation value of total deflection is observed for the developed hybrid models than that of the experimental results.
- The impact of increasing the concrete compressive strength for hybrid slabs increases the proposed load capacity values by an average amount 6.47 to 12.94% for all parametric models, leading to a minor effect on the load capacity. Moreover, the proposed values of the maximum deflection increase by a slightly average amount of 2.98 -20.6% for all slabs models.
- In comparison with the two suggested cases of reinforcement ratio involved in the parametric study, it can be observed that the more increase the reinforcement ratio is increase the ultimate load values by approximately 1.25 and increased the maximum deflection by 22.58%.
- Moreover, this study presented that the smaller the hybrid slab thickness is the smaller the ultimate load values and the closer the maximum deflection values are.

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