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Finite element modelling of concrete beams reinforced with hybrid fiber reinforced bars

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Abstract. Concrete is a heterogeneous composite material made up of cement, sand, coarse aggregate and water mixed in a desired proportion to obtain the required strength. Plain concrete does not with stand tension as compared to compression. In order to compensate this drawback steel reinforcement are provided in concrete. Now a day, for improving the properties of concrete and also to take up tension combination of steel and glass fibre-reinforced polymer (GFRP) bars promises favourable strength, serviceability, and durability. To verify its promise and support design concrete structures with hybrid type of reinforcement, this study have investigated the load-deflection behaviour of concrete beams reinforced with hybrid GFRP and steel bars by using ATENA software. Fourteen beams, including six control beams reinforced with only steel or only GFRP bars, were analysed. The ratio and the ordinate of GFRP to steel were the main parameters investigated. The behaviour of these beams was investigated via the load-deflection characteristics, cracking behaviour and mode of failure. Hybrid GFRP-Steel reinforced concrete beam showed the improvement in both ultimate capacity and deflection concomitant to the steel reinforced concrete beam. On the other hand, finite element (FE) modelling which is ATENA were validated with previous experiment and promising the good result to be used for further analyses and development in the field of present study.

1. Introduction

Fibre reinforced polymer (FRP) composites were first developed during the 1940's for the military and aerospace applications [1]. The characteristics of FRP include high resistance to corrosion, lightweight, high strength-to-weight ratio, high tensile and impact strength, fatigue resistance, non-conductive and magnetically neutral [2]. As a result, FRP have been successfully used in many construction applications such as chemical and waste-water treatment plant, underwater structures, bridges, substation reactor bases, airport runways, laboratories and water tanks [3].

The other application is to strengthen the structurally deficient beams or columns with FRP sheets or plates [4]. Today, applications of FRP in the building industry have realized the increasing popularity in Malaysia. As proven, many construction projects are using FRP water tank to replace the conventional water tank that facing steel corrosion problems. In fact, cost of manufacturing these products is quite high compared to the conventional materials.

Hybrid composite beam (HCB) is a structural member, utilizing several different building materials with dissimilar attributes. Furthermore, the hybrid composite beam is a sustainable technology that combines the strength and stiffness of conventional concrete and steel. In this report, we investigated the flexural performance of hybrid GFRP-steel reinforced concrete beams by using finite element modelling, ATENA. Our analysis model is to predict the load-deflection relationship of the beams. Design models for predicting flexural strength, deflection, and crack behaviour are presented. We analysed beams with different reinforcement ratios and with different ordinate of GFRP and steel, and compared to the control beams including only GFRP and steel reinforcement bar respectively.

2. Literature Review

Conventional reinforced concrete is widely applied in the construction industry owing to the availability and low cost of steel and concrete, the knowledge regarding design, and the vast experience of its use in practise. Due to their different mechanical properties, the behaviour of FRP RC members is quite different to that of traditional steel reinforced concrete [5].

Recently, there has been a rapid increase in the use of Fibre Reinforced Polymer (FRP) bars substituting for conventional steel bars for concrete structures, due to the advantages of noncorrosive characteristic, high strength, and light weight of FRP bars [6]. According to [7] the elastic modulus of FRP bars is much less than that of steel bars. This low elastic modulus leads to higher deflection and larger crack width in FRP bar- reinforced concrete beam that have an equivalent reinforcement ratio to steel-reinforced concrete beams. In addition, while steel bars behave in elastically after yield strength, FRP bars show perfect elastic behaviour up to failure, and fail in brittle manner. In order to overcome this problems in term of deformability and ductility of concrete beams reinforced with FRP bars, alternative solutions of hybrid reinforcing with FRP and steel bars, and using fibre reinforced concrete (FRC) were proposed by [8,9].

Based on [7,10] again, they conclude that the lower stiffness and higher deflection of FRP bar-reinforced beams were controlled and improved by hybrid reinforcing with steel bars. Because of the increased ultimate concrete compressive strain, the GFRP bar reinforced beams with steel and synthetic fibres displayed inelastic and ductile behaviour near the failure, and higher ultimate flexural strength than the beam with no fibres. The steel fibres in concrete and hybrid reinforcing with steel controlled the propagation of cracks and the crack width of FRP-bar reinforced beams. And last but not least, addition of fibres and hybrid reinforcing with steel bars can be possible methods to overcome the low ductility of FRP bar-reinforced beams.

Furthermore, the ductility of RC structure and brittle failure of FRP structure can be resolve by laying the FRP tendons in the corner area where concrete easy corrupted, and it still need to keep on loading to up to the ultimate load after the steel bars yield and shows certain safety factor and good ductility. After all, it is goodish reinforced format state by [11].

Paper studied by [10,12] was investigated accuracy of deflection prediction made by the finite element package ATENA and the design code methods ACI and EC2. Finally G. Kaklauskas stated that deflection was calculated of the beam within load interval ranging from 30 to 90% of the theoretical ultimate load by using the ATENA FE.

3. ATENA Modelling

3.1. Validation of ATENA

Three sets of data RC in direct tension tests have been selected from the literature. The results gathered from the previous experimental stated at methodology which satisfactory demonstrates the accuracy of the FE modelling. Figure 1, 2 and 3 show the trend of the validation of finite element modelling with experimental data.

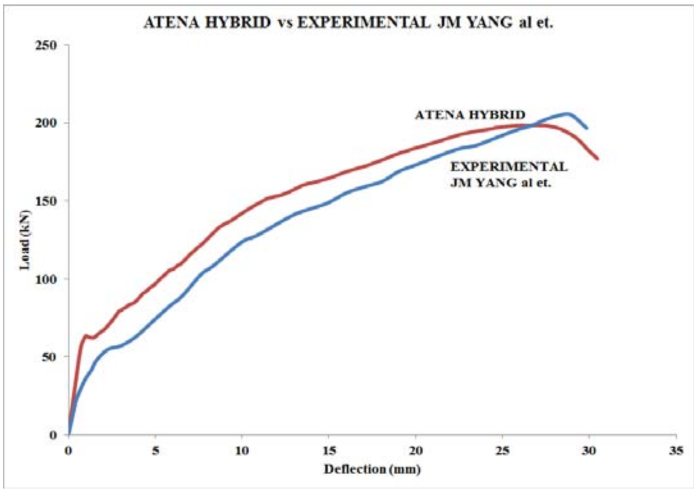


Figure 1. Validation of hybrid beam

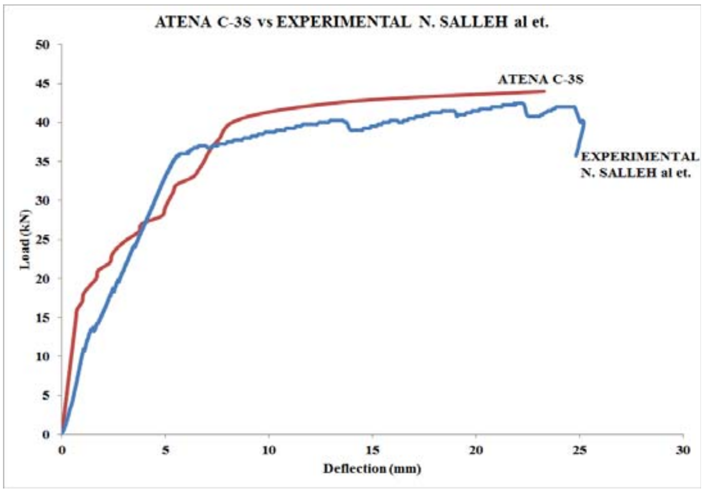


Figure 2. Validation of control steel beam (C-3S)

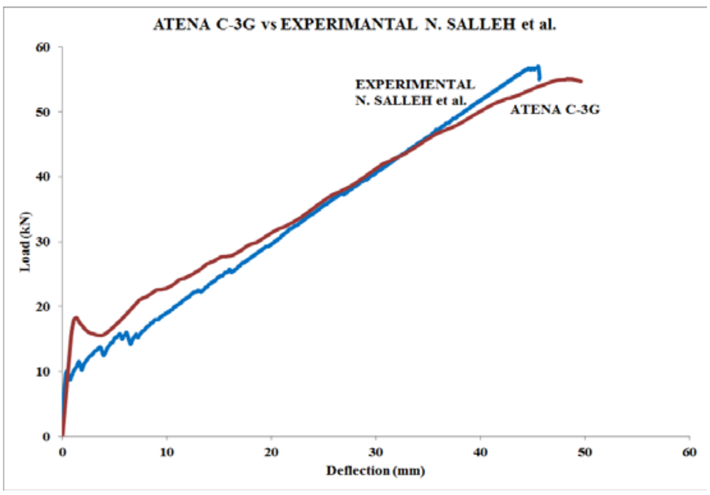


Figure 3. Validation of control GFRP beam (C-3G)

3.2. Details of specimen

Fourteen high-performance concrete beam specimens reinforced with different types of flexural reinforcement and fibre including six control beams were constructed and analysed. Figure 1 shows the details of fourteen beams specimens. All specimens were 2300 mm long with a rectangular cross section of 200 x 250 mm. Group A were reinforced with a layer of reinforcement and Group B and C were reinforced with two layers of reinforcement, and the effective depths of the outer layer (d1) and the inner layer (d2) were 213.5 mm and 200.5 mm, respectively. Each specimen had different combinations of flexural reinforcement of conventional steel bars and GFRP bars.

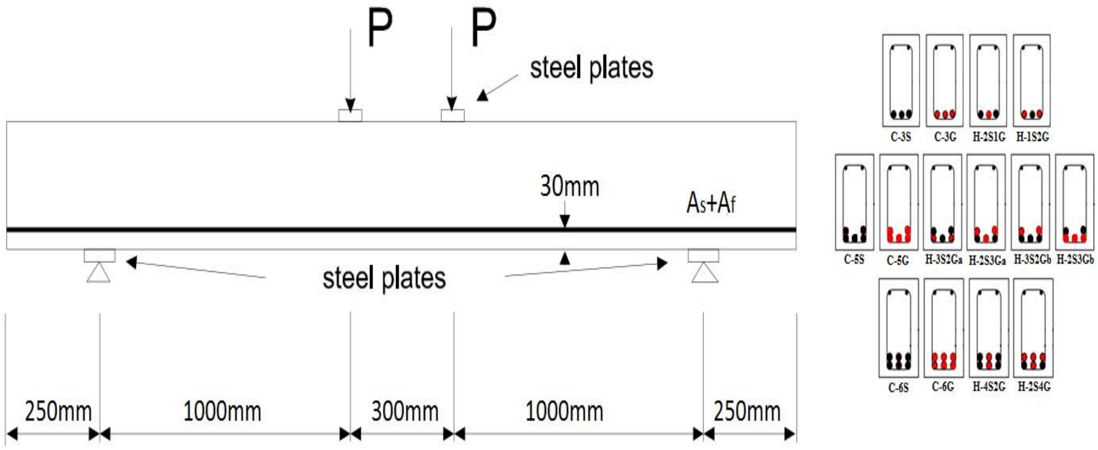


Figure 4. Details of specimens and analyse setup

The first letter in the specimen names indicate the control beam and hybrid beam respectively. All reinforcement used the same diameter which is 12 mm for steel bar and 13 mm for GFRP bar. A 30 mm concrete cover was used, and 8 mm steel bars were used as closed stirrups at 100 mm spacing and as longitudinal compression reinforcements for all specimens. All specimens were designed to fail by concrete crushing to avoid brittle failure. The mechanical properties of concrete, steel and GFRP reinforcement are shown in table 1 below.

Table 1. Mechanical properties of concrete, steel and GFRP reinforcement

Material	Elastic Modulus (GPa)	Compressive Strength (MPa)	Yield Strength (MPa)	Tensile Strength (MPa)
High Performance Concrete	36.95	61.80	-	6.18
Steel bars (12 mm)	200	-	550	-
Steel bars (8 mm)	200	-	250	-
GFRP bars (13 mm)	44.1	-	-	920

3.3. ATENA Setup

Modelling by ATENA was completed by two stages including pre-processing and post processing. In pre-processing stage, there are geometrical model, material selection and boundary condition. The model for finite element analysis will be created during the pre-processing with help of the fully automated mesh generator.

First step before start geometrical modelling is to set the material properties used including High Performance Concrete (HPC), reinforcement bars and steel plate that use for support and reaction. For HPC, SBeta material selected that made a perfect bond between concrete and reinforcement is assumed within the smeared concept. Reinforcement bar will include the steel, stirrup and GFRP respectively. For steel plate, dimension 100 mm x 200 mm x 30 mm will be used and the material use is Plane Elastic Isotropic by use Hooke's Law. All properties of material are entered by information given above.

Next step is to form the geometrical model including the geometrical joint that connected to the boundary lines. Then the model will mesh with 0.005 m size of element. Boundary condition that used in this analysis is force and prescribed deformation which located at the support and reaction respectively. Three monitoring point also included in the modelling as indicator to monitor the analysis while running by the Newton-Raphson Method chosen. The overall review of modelling is shown at figure 5 below.

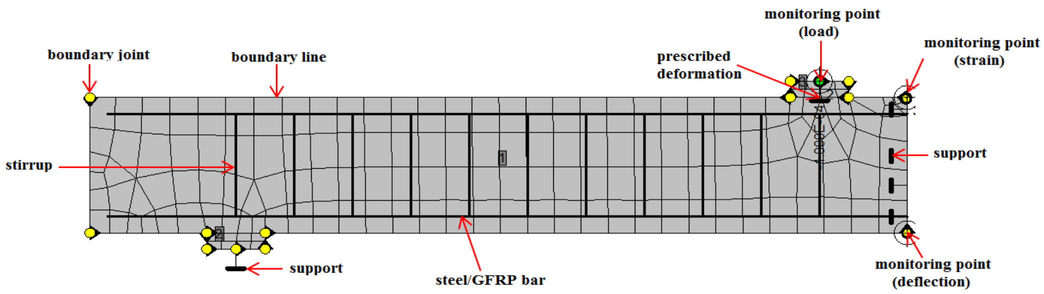
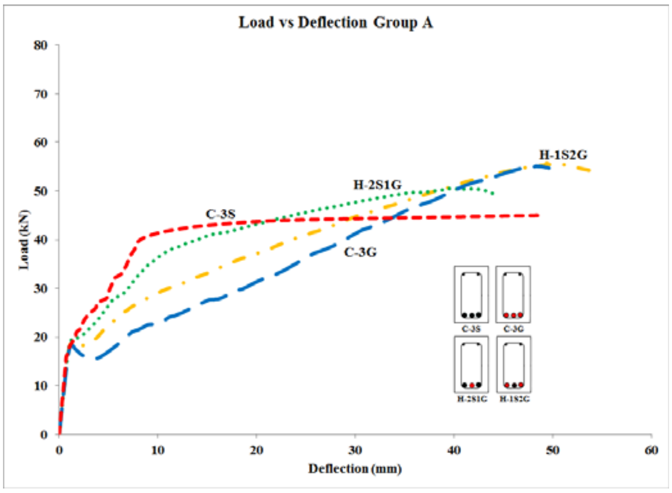


Figure 5. Overview the model setup in ATENA

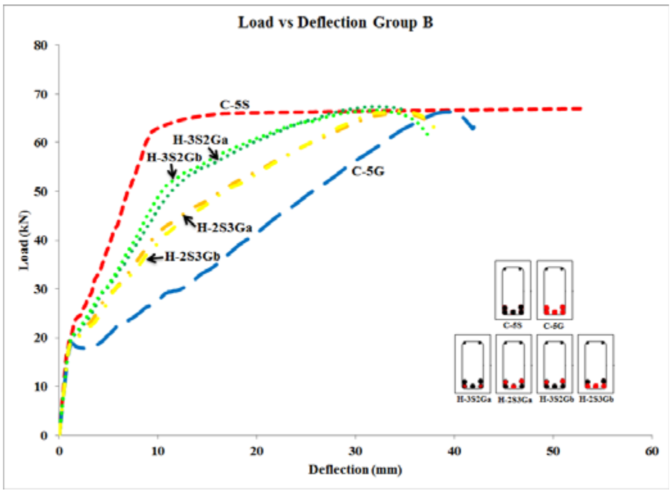
4. Results and Discussion

4.1. Load-Deflection behaviour of specimens

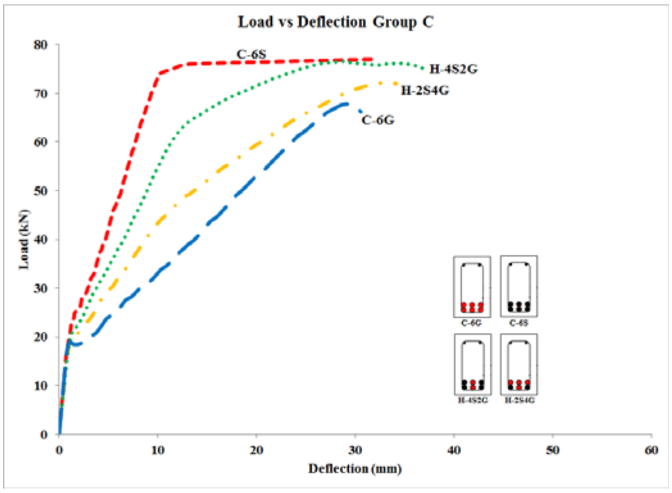
Figure 6 (a) to (c) shows the load versus mid-span deflection analysis, while table 2 summarizes the loads and mid-span deflection of the theoretical and ATENA value as well as the failure mode for all beam specimens. Initially all beams show relatively linear elastic behaviour up to the cracking load when the concrete cracked at the tension face. Due to the low elastic modulus of GFRP bars, the stiffness of the beam was reduced faster with larger deflection.



(a)



(b)



(c)

Figure 6(a) – (c). Load versus deflection analysis

Table 2. Summarize of analysis results

Group of Specimen		P_{theo} (kN)	δ_{theo} (mm)	P_{ATE} (kN)	δ_{ATE} (mm)	Δ P (%) (kN)	Δ δ (%) (mm)	ρ (%)
A	C-3S	32.77	22.62	45.00	48.76	0.73	0.46	0.79
	C-3G	60.78	41.95	55.14	40.51	1.10	1.04	0.93
	H-2S1G	42.49	29.33	50.47	33.36	0.84	0.88	0.84
	H-1S2G	51.83	25.77	49.70	29.74	1.04	0.87	0.89
B	C-5S	50.77	35.04	67.00	42.10	0.76	0.83	1.37
	C-5G	89.81	61.99	65.25	34.02	1.38	1.82	1.60
	H-3S2Ga	67.55	46.62	67.38	32.23	1.00	1.45	1.46
	H-2S3Ga	75.35	52.01	65.96	35.21	1.14	1.48	1.51
	H-3S2Gb	67.55	46.62	66.01	34.33	1.02	1.36	1.46

	H-2S3Gb	75.35	52.01	65.94	36.10	1.14	1.44	1.51
C	C-6S	59.67	41.19	77.00	32.27	0.88	1.41	1.64
	C-6G	102.95	71.06	67.78	29.22	1.34	2.20	1.92
	H-4S2G	75.64	52.21	76.11	33.52	1.05	1.56	1.73
	H-2S4G	90.07	62.17	72.60	33.52	1.24	1.85	1.83

Although the effect of plastic strains is less significant for under-reinforced members, deflection are underestimated by the method at large loads [12]. Thus, the accuracies of the theoretical analysis and the FEA model for beams with low or high effective reinforcement ratios need further verification according to the [13] that have the same results.
After first flexural cracking, the stiffness of the cracked was reduced, and each specimen started to behave differently depending on the combination of the flexural reinforcement. In term of the control beam, we can see they react differently when the increasing of the GFRP bars. In the time the GFRP bars increasing to five and six bars the strength of the beam same and reduce with the strength of the steel bars respectively.
Hybrid beams with different reinforcement ratio and ordinate of reinforcement show a high potential in the comparison in the group A instead of the group B and C. Meanwhile, the GFRP bars react as good bond with concrete when it is set at the outer of the tension [14]. Furthermore, the bonding of the GFRP bars getting low when the quantity is increase. The load carried by beam reinforced with more GFRP bars are getting low than the beam reinforced with more steel bars. This conclude that the beam reinforced with GFRP bars already achieve the maximum strength according to the increasing number of the bar in group B. Hybrid beams showed a significant improvement in terms of beams deformability under service load conditions, since the beams were over-reinforced, the contribution of steel bars to increase the flexural capacity was less than 15% [14].

4.2. Cracking behaviour
Sections
The depth of cracks in beam reinforced with steel bar was very short, while the cracks in beams reinforced with GFRP bar propagated quite deeply into the compression zone. This indicates that immediately after the formation of the first cracks the neutral axis shifted up very near the top compression of the GFRP bar-reinforced beams. Cracks in hybrid reinforced specimens with steel bars and in GFRP reinforced specimens were shallower than those in beam reinforced with GFRP bar only. This indicates that the deep propagation of cracks in the GFRP bar-reinforced beams can be restrained by hybrid with steel bars. Figure 7 shows the pattern of cracking for hybrid beam that perform well than other beams.

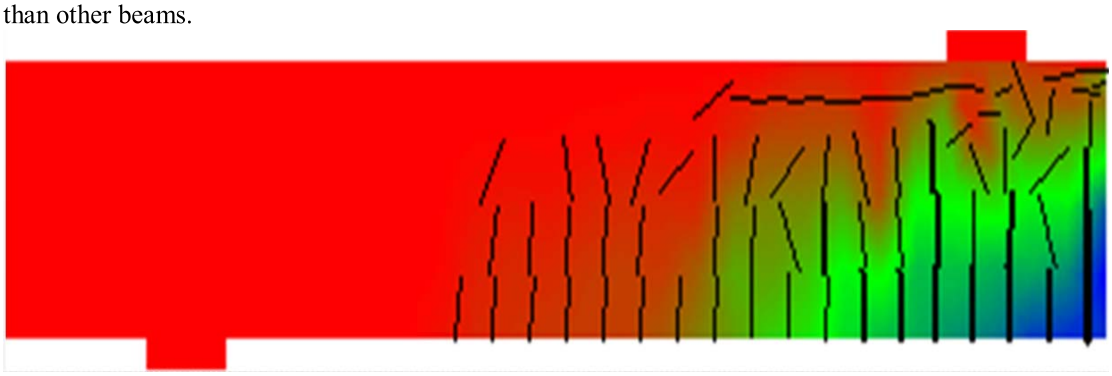


Figure 7. Crack Pattern of Hybrid Beam

Crack behaviour is summarizes in the table 3. As expected, the beam contains GFRP bar will crack before the beam contain steel bar because of the lowest modulus of elasticity of the GFRP reinforcement bar.

Table 3. Cracking Behaviour and Mode of Failure

Group of Specimen		P_{cr} (kN)	Failure Mode
A	C-3S	17.00	Flexural
	C-3G	15.90	Flexural
	H-2S1G	16.37	Flexural
	H-1S2G	16.14	Flexural
B	C-5S	18.00	Flexural
	C-5G	16.03	Flexural
	H-3S2Ga	16.62	Flexural
	H-2S3Ga	16.50	Flexural
	H-3S2Gb	16.74	Flexural
	H-2S3Gb	16.38	Flexural
C	C-6S	18.00	Flexural
	C-6G	16.09	Flexural
	H-4S2G	16.93	Flexural
	H-2S4G	16.59	Flexural

All beams failed in the flexural tension mode besides the major factor for the failure of beam is the concrete failure in the compression zone. Cracking pattern indicated that the steel reinforced concrete beam was more ductile compared to the GFRP reinforced concrete beam.

5. Conclusion

i. Hybrid GFRP-steel reinforced concrete beam had achieved ultimate load at the same time higher compared to the conventional concrete beam.
ii. The lower stiffness and higher deflection of FRP bar-reinforced beams were controlled and improved by hybrid reinforcing with steel bars.
iii. ATENA 2D was employed to simulate the structural behaviour of the hybrid reinforced GFRP-steel beams.
iv. Hybrid GFRP-steel reinforced concrete beams had good bond performance when installing the GFRP bars as near as possible to the outer surface of the concrete element, which is beneficial in term of structural performance of the reinforcing bar.
v. The steel bars increased the ductility of hybrid GFRP-steel reinforced concrete beams.

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