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NUMERICAL MODELLING OF CFRP STRENGTHENED REINFORCED CONCRETE BEAMS UNDER IMPACT LOADING

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Abstract: In the recent years, externally bonded carbon fibre reinforced polymer (CFRP) composites are commonly used to strengthen existing reinforced concrete (RC) structures. In everyday practice, there are many situations under which deteriorated structures are subjected to impact loads. Thus, it is essential to have a comprehensive understanding of the response of CFRP strengthened RC beams subjected to impact load. This paper aims at providing a numerical model which is able to represent the behaviour of this kind of structures. It is worth noting from previous studies that CFRP strengthened RC beams can fail in several scenarios including flexural and shear failure in concrete (or mix between them), debonding of the CFRP layers and rupture in the CFRP. Thus, it is important to build a numerical model can capture all possible failure modes that could occur in the case of CFRP strengthened RC beams subjected to impact loads. The damage criteria were used for the concrete, CFRP and contact between concrete and CFRP to capture the failure that may occur. The proposed numerical model was then validated against set of samples tested in previous studies. It was found that the numerical model can capture the test results with high level of accuracy.

Keywords: *Finite element, RC beam, Impact load, CFRP, Strengthening*

النمذجة العددية للاعتاب الخرسانية المسلحة المقواة بالياف الكاربون المعززة للبوليمر تحت تاثير الحمل الصدمي

الخلاصة: التقوية باستخدام الياف الكاربون المعززة للبوليمر تستخدم بشكل شائع حاليا لتقوية العناصر الانشائية الخرسانية المسلحة الموجودة. هناك العديد من الحالات التي يتعرض فيها المنشائات الى احمال صدمية. لذلك من المهم معرفة السلوك الصدمي للاعتاب المقواة. هذا البحث يهدف الى توفير نموذج عددي قادر على تمثيل هكذا انواع من المنشاءات. اشارت الدراسات السابقة الى ان الاعتاب المقواة ممكن ان تفشل باشكال مختلفة منها فشل الانحناء والقص للخرسانة او كليهما، انفصال طبقة التقوية من العتب و الفشل في طبقة التقوية. لذلك من المهم أنشاء نموذج عددي قادر على محاكات جميع انواع الفشل الممكنة في مثل هكذا حالات. معايير فشل خاصة استخدمت لتعريف فشل الخرسانة وطبقة التقوية وكذلك منطقة الاتصال بينهما. واخيرا تم التحقق من صحة تمثيل النموذج العددي بمقارنته مع نتائج من دراسات سابقة. وقد وجد ان النموذج العددي قادر على تمثيل سلوك الاعتاب الخرسانية المقواة تحت تاثير احمال الصدمة.

1. Introduction

Recently, as a result of increasing terrorism activities and threats imposed a notable danger on the civil infrastructure, blast and impact resistance design of structures has become one of the main priorities for researchers and engineers. Carbon fibre reinforced

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polymer (CFRP) has been used as an excellent material in strengthening or retrofitting existing structures such as beams, columns and slabs. This use has become popular worldwide due to superior properties of CFRP materials. The performance of FRP strengthened beams subjected to static loads has been widely studied in the literature [1-3].

However, up to now, limited studies have been found on behaviour of CFRP strengthened beams subjected to impact load. In particular, the impact performance of concrete beams strengthened with CFRP is of interest. Among these studies, Erki and Meier [4] carried out an experimental work on 8-m-long RC beams strengthened with CFRP tested under impact load. The impact load was applied by raising up one of the beam ends and dropping it on the support. The specimens failed by debonding of CFRP layers, while the flexural strength of the strengthened beams was enhanced and their maximum deflection was reduced.

A similar observation was drawn on another study [5] where the debonding together with shear failure were the typical failure mode for the tested samples. Inappropriate surface preparation seems to be the reason for the debonding because the concrete surfaces were only cleaned by acetone in the later study. For further investigation, the same authors carried out another research with similar beam design consisted of testing 27 beams [6]. The sandblast method was used to remove the weak layer from the concrete surfaces before clean the surfaces with acetone. The experimental results showed that the beams failed with shear, while no CFRP debonding was observed in this set of experiments. In both of the above studies conducted by Tang and Saadatmanesh [5, 6], CFRP was applied on the top and bottom surfaces of the concrete beams without using wrapped CFRP.

On the other hand, a few studies has been investigated the shear behaviour of CFRP retrofitted RC beams under impact loading [7-9]. Among these studies, Pham and Hao [7] tested a series of CFRP strengthened RC beams under static and impact loads with different CFRP configurations including CFRPU-wraps and 45^{o}-angle wraps. These samples were designed to fail in shear. The experimental results showed that all beams tested under impact load failed in shear.

Another experimental study conducted by the same authors but for beams designed to fail in flexure mode by providing relatively large shear resistance (3.42-4.08 higher than beam flexural resistance). The experimental programme consisted of testing a series of samples under two loading rates (quasi-static and impact). The test results demonstrated that even though the samples were designed with enough shear capacity, the samples tested under impact load failed by combined shear and flexure modes. Further examination of the impact response of CFRP strengthened beams revealed that CFRP strengthening technique is able to prevent the shear failure of the beams tested in this study, but by increasing the CFRP reinforcement ratio up to that required by the ACI specification.

In summary, in the case of RC beams subjected to impact loading, the shear mechanism is typically more critical even if these beams are designed to fail with flexure under static loading condition. These studies revealed that RC beams, which failed in a ductile manner (flexure) under static loading condition, shifted to a brittle failure (shear) when these beams subjected to impact loading. It can be seen from the above studies that the shear failure is dominated in the case of RC beams under impact loading. However, shear enhancement of CFRP strengthened RC beams under impact load are still limited. This study will thus aim to provide a comprehensive understanding for the impact behaviour of CFRP strengthened RC beams. The primary objective of this research is to provide a FE model which is able to represent the behaviour of CFRP strengthened RC beams under impact load. Then this model will be used to achieve the following objectives in further research: (1) investigation of a wide range of CFRP configurations to enhance RC beams under impact load for beams designed to fail in flexure and shear; (2) energy absorption improvement of CFRP strengthened RC beams under impact load; and (3) examination of different parameters, which have not been covered in previous studies such as mechanical properties of materials (concrete and CFRP), applied energy and its components (velocity and mass)…etc.

2. Experimental Work Description

In order to validate the numerical model, an experimental work from the literature is used. A series of CFRP strengthened reinforced concrete beams tested under impact load by Pham and Hao [9] is used in this paper. The width and height of the tested beams were 150 mm and 250 mm respectively with a total length of 2200 mm (1900 mm effective span). The compressive strength of the concrete was 46 MPa at 28-day age. Two deformed bars with 12 mm in diameter were used in the top of the beam, while the bottom of the beam was reinforced by two deformed bars of 10 mm in diameter. 10 mm plain reinforced bars were used in shear reinforcement. The distance between the stirrups was 125 mm for whole beam length. The yield strengths of the deformed and plain reinforcements were 500 and 250 MPa, respectively. The width of CFRP layer used in the experiments was 75 mm with a nominal thickness of 0.45 mm. The tensile strength and elastic modeulus were 1548 and 89000 MPa respectively.

Four samples were simulated in this study. These samples include an un-strengthened sample (reference beam (RB)) and two samples strengthened with one and two layers of CFRP in the longitudinal direction (NL1B and NL2B respectively) and a sample stengthened with two layers of CFRP in the longitudinal direction and seven U-strips in the transverse direction (more information about the naming system can be found in [9]). The impact tests were performed by dropping a mass from a specific height onto beams mid-span. A solid cylinder weighing 203.5 kg was dropped from 2 m height to produce 6.28 m/sec theoretical velocity.

3. Numerical Modelling

The RC beams investigated in this paper were modelled using three-degree of freedom (8-nodes) solid elements (C3D8R) available in ABAQUS/Explicit element library [10]. A two-node linear displacement (T3D2) truss element was employed to model the internal reinforcement (main reinforcement and stirrups). The impactor was modelled using a discrete rigid body with a reference point to provide the mass of the impactor. The discrete rigid body was used because there is no deformation occurred in the experimental test [9]. Shell elements (S4R) were employed to represent the CFRP. The S4R element has six degrees of freedom per node. In order to model the contact region between CFRP and the concrete beam, cohesive elements were used for this purpose. Cohesive elements (COH3D8) have six degrees of freedom per node. This type of element was commonly used to model this kind of contact zone in the similar cases such as Al-Zubaidy, et al. [11]. The damage plasticity model was used to introduce the concrete behaviour because of its capability to anticipate the behaviour of concrete up to failure [12]. The modelling of concrete was passed through two steps. In the first step, the elastic modulus and Poisson's ratio were defined, while in the second step the damage plasticity model was adopted to define the nonlinear portion of the stress-strain curve of the concrete. The following parameters were introduced in addition to the uniaxial stress-strain curve of concrete:

- The dilation angle which is ranged from 12^o and 30^o [10]. In this study, the dilation angle was assumed equal to 20^o [13].
- Eccentricity which is assumed to be 0.1 (default value in ABAQUS).
- Viscosity parameter =0 [13].
- The ratio of initial equilbiaxial strength to initial uniaxial strength when the default value was used (1.16).

Both deformed and plain steel reinforcements were defined as an elastic perfectly plastic material by defining the Young's modulus and yield strength of the bars which were discussed in the previous section.

The linear elastic response of CFRP was defined by using a lamina model which is required to define the elastic moduli, shear moduli in two directions and Poisson's ratio. In order to introduce the damage in the CFRP in this model, ABAQUS/Explicit offers Hashin's failure criteria [14] which was commonly used to define the damage in the composite materials. This damage model is defined by providing the longitudinal and transverse tensile and compression strengths of CFRP in addition to the longitudinal and transverse shear strengths. These values which are listed in Table 1 were gained from the simulated experimental work [9] and another work in the literature [15].

Table 1. Material properties of the CFRP sheet

Property	Value
Density*	1600 kg/m3
E1 Elastic modulus in the longitudinal direction	89 GPa
E2 Elastic modulus in the transverse direction*	17 GPa
G12 In-plane shear modulus*	6 GPa
Longitudinal tensile strength	1548 MPa
Longitudinal compressive strength*	1200 MPa
Transverse tensile strength*	50 MPa
Transverse compressive strength*	250 MPa
Longitudinal shear strength*	70 MPa

*material properties were obtained from Dolce [15]

Regarding the contact between the concrete beam and CFRP, the traction-separation model was used. This model can also be defined in two steps. In this first step, the linear elastic part can be defined by introducing the values of the elastic modulus and shear moduli in the longitudinal and transverse directions, while the second part represents the damage criteria. In this part, ABAQUS/Explicit offers four different damage initiation criteria. The quadratic nominal stress criteria was employed in this study which is commonly used in similar cases [11, 16].

The interaction between the impactor and the analysed beams was defined by using the contact pair option available in ABAQUS/Explicit. In order to introduce the contact pair algorithm ABAQUS/Explicit requires the master and slave surfaces to be specified. There couple of rules should be followed to define these surfaces. Among these rules the slave surface should be the softer underlying material. Therefore, the impactor was treated as a master surface, while the impacted member (RC beam) was chosen to be a slave surface.

4. Validation of the Numerical Model

In order to provide a comprehensive understanding for the impact behaviour of CFRP strengthened concrete beams, the capability of the numerical model to capture the real response of the studied case should be verified in the beginning. The validation of the numerical model includes the comparisons of the numerical impact force-time history, peak impact force, displacement-time history, maximum displacement, and failure modes with corresponding experimental results.

The impact force-time histories for the simulated beams are plotted in Figure 1. This figure illustrates that the typical impact force-time history consisted of three parts. The first part starts from the beginning of the test until the impact force reaches the peak impact force. After that the second part (so-called plateau) starts in which most of impact energy is dissipated due to its relatively long duration. The impact force then gradually decreases until reaches zero when all impact energy is dissipated. This part called the unloading part.

The comparisons between the impact force-time histories gained from experimental and numerical results demonstrated that the numerical model is able to capture the force-time history of the beams with accepted level of accuracy as shown in Figure 1. It can also be seen from this figure that the impact duration obtained from numerical simulation was slightly less than that obtained from physical tests. The impact duration of the simulated beams was found to be at maximum of ~ 30% less than the corresponding value obtained from experimental results. This variation may be related to the fact that the fixity in the tests and simulation is quite different. In addition, the damping force introduced by the experimental test rig could also be another reason for this variation. However, this variation was not found to be significant in the present study when compared to other studies when a similar simulation was conducted.

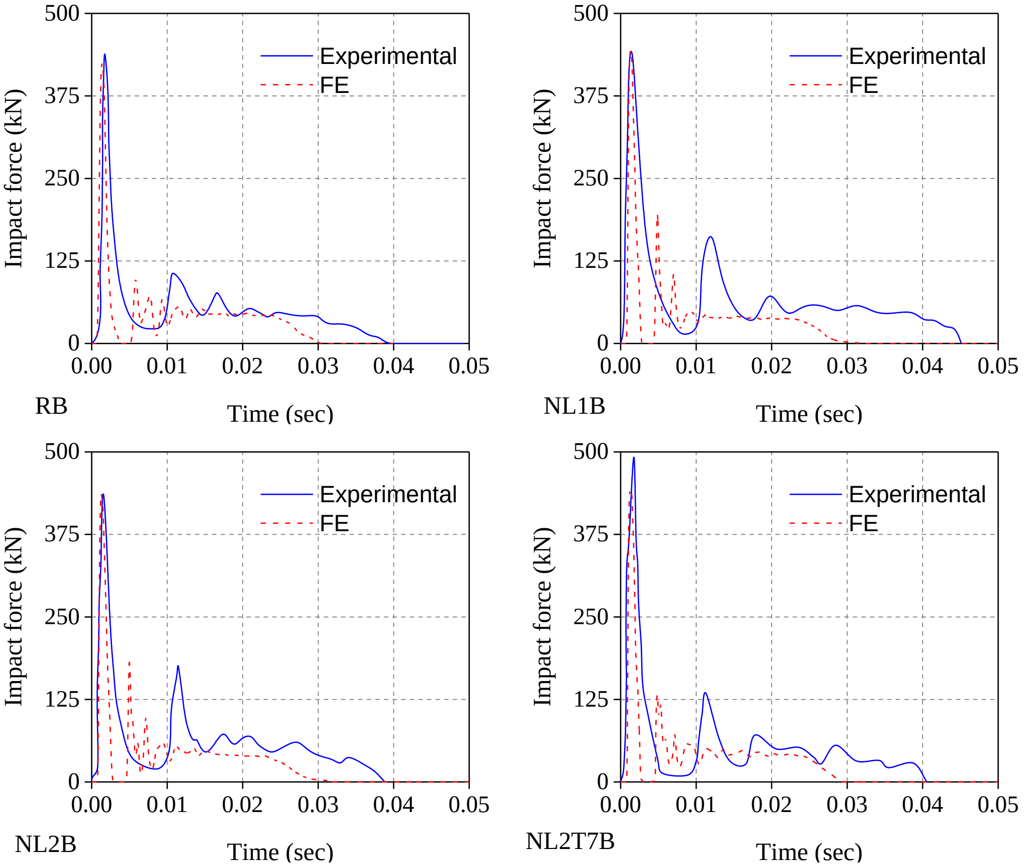


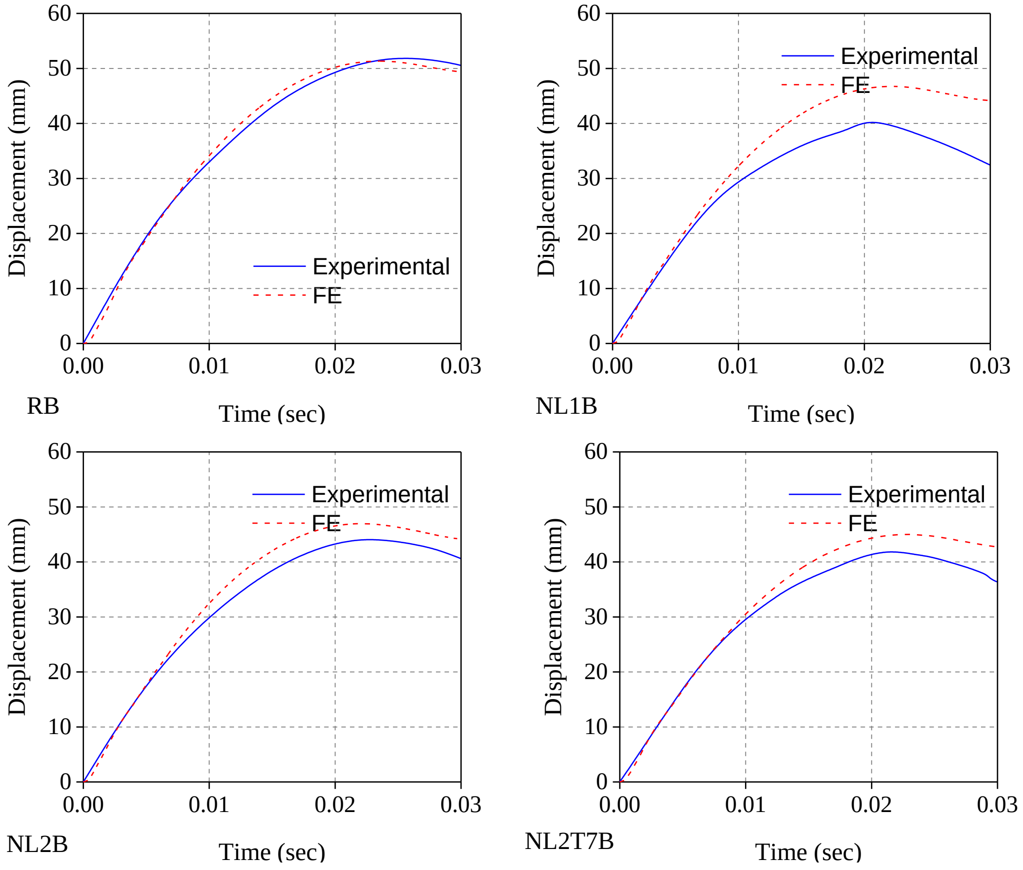
Figure 1: Comparison of experimental and FE impact force-time histories for CFRP strengthened RC beam

Regarding the peak impact force, the comparison between the values obtained from the simulation and experimental results demonstrates that the predictions of the numerical model are agreed well with the corresponding experimental values as listed in Table 2. It can be noted from this table that the numerical results has less than 10% in maximum variation in comparison with corresponding experimental results.

Table 2: Summary of the simulation results

Sample	Peak impact force (kN)			Maximum displacement (mm)		
	Ex.	FE	Difference %	Ex.	FE	Difference %
RB	453	429	5%	52.3	51.3	2%
NL1B	470	441	6%	41.1	46.1	-12%
NL2B	464	445	4%	44.2	46.9	-6%
NL2T7B	492	451	8%	41.7	44.9	-8%

In terms of displacement-time histories, the numerical results showed very good agreement compared to the corresponding experimental results apart from sample NL1B, when there was a significant difference in the maximum displacement. However, the difference is not more than 11% as listed in Table 2. Thus, generally the numerical model was able to predict the displacement-time history of the impacted beams with a reasonable level of correlation.



RB NL1B

NL2B NL2T7B

Figure 2: Comparison of experimental and FE displacement-time histories for CFRP strengthened RC beam

It was reported in the experimental results that the beams strengthened with CFRP being laid longitudinally failed with CFRP debonding. Figure 3 illustrates the debonding of the CFRP layer from the concrete beam at 0.016 sec after the impact initiation. For the un-strengthened beam (RB), the experimental failure mode was governed by both shear and flexural modes which is quite comparable with that obtained from numerical modelling as shown in Figure 4. This figure shows the damage in the concrete beam as mentioned in the beginning of this paper. The distribution of damage contours in Figure 4 represents the vertical (flexural) and diagonal (shear) cracks.

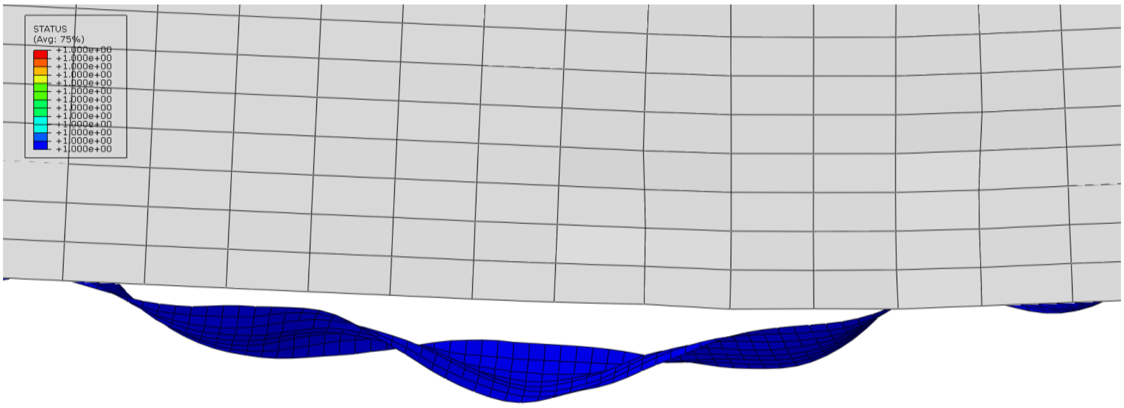


Figure 3: Failure mode of beam NL1B

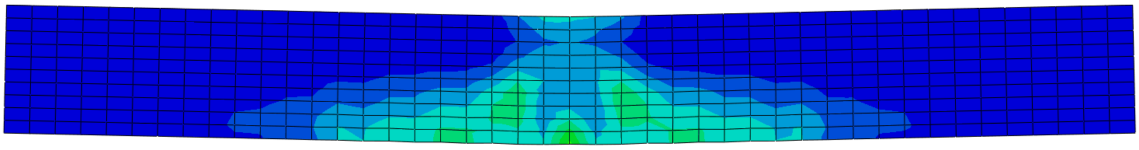


Figure 4: Failure mode of beam RB

To sum up, the presented numerical model is capable of capturing the response of the CFRP strengthened RC concrete beam under impact loading.

5. Conclusions

Depending on the simulation results presented in this paper, it can be accepted that the numerical model is capable of simulating the behaviour of CFRP strengthened RC concrete under impact load. This conclusion was drawn after comparing the simulation results with the corresponding experimental results – impact force histories, displacement histories, residual displacement and failure modes – and finding a good correlation. Thus this model can be used in further simulations to investigate the response of CFRP strengthened RC members subjected to impact loading to extend the studies presented in the literature by proposing another group of CFRP configurations to improve RC beams performance under impact load. In addition to study a range of parameters that might affect the impact behaviour of CFRP strengthened RC beams.

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