Numerical Analysis of Concrete Beams Strengthened with FRP Laminates under Impact Loading

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Abstract:
Most researches on application of composite materials in civil engineering during the past decade have been concentrated on the behaviour of structural elements under static loads. Fibre Reinforced Polymers (FRP) due to their excellent mechanical properties, durability and impact resistance are very attractive for such applications. In present numerical study, the use of FRP laminates for strengthening concrete beams under the impact loading is investigated. Finite element software, Abaqus, was used. Two types of fibre (carbon and aramid) were considered and different lengths for FRP laminates were examined. The study was validated using the result of previous work done on a series of 21 retrofitted concrete beams using FRP laminates under impact loading. Similar to the experimental study, the impact load was considered as a drop weight from a specific height on the top surface of the beam. Results indicated that the gain in strength depends on the type, length, and weight and material properties of the composite laminate.

Keywords: Impact, FRP, Concrete, Strengthening, Drop weight

1. Introduction:
During the past decade, impact protection has become an important parameter in design of every structure. Structural engineers have tried to develop economical and efficient solutions for this problem while taking into account the limited budget available. Replacing the impact deficient infrastructures requires significant financial resources and considering the limitations, developing cost effective methods are necessary. Retrofitting of the existing structures in order to avoid replacing them is a realistic remedy. Fibre Reinforced Polymers (FRP) due to their excellent mechanical properties, durability and impact resistance are very attractive to be used for such applications.
In present numerical study, the use of FRP laminates for strengthening Reinforced Concrete (RC) beams under impact loading acting at the midspan of a retrofitted beam is investigated. Finite element software, Abaqus, was used for the non linear analysis and parameters such as: types of laminates and different lengths have been considered. Two types of fibres (carbon and aramid) were considered for different FRP laminates.
2. PREVIOUS WORKS

Almost all low-velocity impact research has focused on pure composite structures. Only one study was found on impact behaviour of concrete beams strengthened with composite laminates. Erki and Meier conducted tests on four 8-m-long reinforced concrete beams strengthened for flexure [1]. Two beams were strengthened with carbon FRP (CFRP), and the other two with steel plates. Impact loading was induced by lifting one end of a simply supported beam and dropping it. Strain rate of loading ranged from an average of 0.7 s\(^{-1}\) to a maximum of over 0.84 s\(^{-1}\). They found that beams externally strengthened with CFRP laminates performed well under impact loading, although they could not provide the same energy absorption as the beams strengthened with steel plates. Caprino and his colleagues investigated the influence of material thickness on the response of carbon fabric/epoxy panels to low velocity impact [2]. The force and absorbed energy at the point of delamination initiation, the maximum force and related energy, and the penetration energy were evaluated. From the experimental results, they concluded that all these quantities, except the energy for delamination initiation, followed the same trend, increasing to the power of approximately 1.5 with increasing plate thickness. Tsubota and his colleagues experimentally investigated the inelastic behaviour of reinforced concrete (RC) Panels under high-speed loading using 1/6 scale specimens. This study was conducted to ensure the safety of nuclear-related RC structures subjected to an aircraft impact, focusing on the effects of rebar ratio and the adequacy of rebar lap splices. They concluded that the maximum capacity of the specimen under high speed loading increases by 15% over that of the static case. The RC panel (reinforcement ratio: 0.47%) showed more ductile behaviour under dynamic loading than under static loading.

3. MODELING AND MATERIALS

The reference structure in this study was a concrete beam which retrofitted by two kinds of FRP laminates (carbon and aramid). Each beam was experienced impact load by dropping down the steel cylinder from different heights. The midspan deflection and reaction force at supports was determined and compared with the tests specimens. The behaviour of three different lengths of FRP laminates was examined. The specifications of specimens and mechanical properties of the materials were considered similar to a study done by Tang and Saadatmanesh as follows [4].

3.1.1 Modelling

The reinforced concrete beams under investigation is a 203×95 mm cross section, with 1.98 m length, and has two No. 3 longitudinal reinforcements (d = 9.5 mm). The beams had no shear reinforcement because the span/depth ratio was fairly large (about 20). Two beams were strengthened with CFRP laminates on the top and bottom faces; two beams were strengthened with CFRP laminates on the top and bottom faces; and the other two were strengthened with aramid FRP (AFRP) laminates. One beam was not strengthened and was used as the control specimen. Fig. 1 shows the design details of the test specimens and the beam cross section. Both carbon and aramid fabrics are unidirectional; fibre orientation is parallel to the direction of span. One layer of fabric was used to four beams. The polymer considered for making the FRP was a typical epoxy. Because of the vibration induced by impact loading, the top and bottom faces of the beams would experience cyclic tensile and compressive stresses; therefore, composite laminates were bonded on both faces. The beams strengthened with AFRP laminate were labelled TB1 and TB3, those with CFRP laminate were labelled TB2 and TB4, and the control beam was labelled TB5.
3.1.2 Materials

The concrete compressive strength was 27.6 MPa, and the initial elastic modulus of concrete was 24.9 GPa. The yield strength of the bars was 275.8 MPa, and the elastic modulus of reinforcement was 200 GPa. The physical and mechanical properties of the composite laminates are listed in Table 1.

<table>
<thead>
<tr>
<th>Composite</th>
<th>Thickness (mm)</th>
<th>Weight (g/m²)</th>
<th>Ultimate strain</th>
<th>Ultimate strength (MPa)</th>
<th>Modulus of elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP</td>
<td>0.67</td>
<td>599</td>
<td>0.014</td>
<td>1,035</td>
<td>85.7</td>
</tr>
<tr>
<td>AFRP</td>
<td>0.43</td>
<td>307</td>
<td>0.017</td>
<td>460</td>
<td>37.6</td>
</tr>
</tbody>
</table>

3.1.3 Loading

The impact load was considered as a 222 N steel cylinder (127 mm diameter) was dropped onto the top surface of each beam from various heights. The geometric shape and material of the drop-weight have a strong influence on the response of the test specimen, which has been discussed in the literature [5]. Considering the relative stiffness of steel and concrete, the deformation of the drop-weight caused by impact was neglected. To get point contact between the steel cylinder and beam, the cylinder was curved surface at the cylinder’s bottom face. For beams TB1 and TB2, the cylinder was repeatedly dropped from heights of 1.52, 1.83, 2.44, 2.74, 3.05 and 3.66 m.

4. ANALYSIS

In order to analyse the beams under impact load, Explicit Analyser of Abaqus is used. Maximum values of the parameters such as deflection and stress for reference beams and retrofitted beams with different FRP laminates were determined and compared [6].

4.1 Finite Element Analysis

First, the reference reinforced concrete beam (TB5) and other two retrofitted concrete beams (TB1 & TB2) were modelled and after analysis, maximum values of deflection and reaction forces were validated. Then, the reference beams are assumed to be strengthened by FRP laminates with different lengths and analysed. Three specific lengths include 1.828, 1.528 and 1.228 m was examined.

4.1.1 Validations

Parameters considered for comparison between the behaviour of the test specimen and beams modelled included: maximum deflection and reaction force.
For validating the models, two base parameters are used. Three base models, TB5, TB1 and TB2 were validating by maximum deflection and reaction force which indicates by figures 2 till 7.

4.1.1.1 Deflection
One parameter that can be used for validation of the numerical models with the existing experimental results is midspan deflection of the specimens. As it is shown in Figures 2 through 4, the model predicted the midspan deflection of the control beam in addition to retrofitted beams with AFRP and CFRP laminates under impact of the drop-weight obtained from the previous experimental studies fairly well.

![Figure 2. Midspan Deflection for Repeated Drops of TB5 (Control Beam)](image)

![Figure 3. Midspan Deflection for Repeated Drops of TB1 (AFRP)](image)

![Figure 4. Midspan Deflection for Repeated Drops of TB5 (CFRP)](image)
4.1.1.2 Reaction Force
Another parameter that can be used for validation of the numerical models with the existing experimental results is the reaction force at the support of the beam. Similar to the result shown in the previous section, the reaction forces determined by the numerical study agreed with the experimental results of control and retrofitted beams with AFRP and CFRP laminates under impact of the drop-weight as shown if Figures 5 through 7.

4.2 Analysis of the Results
Parameters considered for comparison between the behaviour of the retrofitted beams and control beams included: maximum midspan deflection, concrete and FRP stresses and damage index in FRPs.
4.1.2.1 Deflection
As Figure 8 represents, the effect of using FRP laminates made with aramid and carbon fibres for strengthening RC beams with different length of laminates is apparent. Effect of retrofitting technique is such that maximum midspan deflection of the beams decreases from average of 18.0 mm in unretrofitted condition to 10.0 mm in the most effective case. The effect of the type of FRP is more obvious by increasing the height of the drops. In Figure 9 and Figure 10, the effect of the longer laminates on the midspan deflection were displayed.

Figure 8. Midspan Deflection for Repeated Drops of Specimens

Figure 9. Midspan Deflection for Repeated Drops of Specimens Retrofitted with AFRP Laminates with Different Lengths

Figure 10. Midspan Deflection for Repeated Drops of Specimens Retrofitted with CFRP Laminates with Different Lengths
4.1.2.1 Stress
The tensile stress is concrete developed by the impact would cause the cracking and is the main source of the damage in retrofitted specimens. In addition, the stress in FRP laminates and tat the interface, should be controlled in order to determine the time and seriousness of debonding.

4.1.2.1.1 Tensile Stress in Concrete
The tensile stress in concrete determines the initiation of the growing cracks at bottom surface of beams. The cracking stress limits by 3.15MPa. Figure 11 and Figure 12 show the trends of various tension stress in concrete which retrofitted by two types of FRP laminates. These figures show that retrofitted beams by AFRP laminates resist higher height of drops in order to reach the same stress as the one retrofitted with CFRP laminates and therefore may absorb more energy before failure.

![Figure 11. Tensile Stress in Concrete for Repeated Drops (AFRP)](image)

![Figure 12. Tensile Stress in Concrete for Repeated Drops (CFRP)](image)

4.1.2.2 Stress in FRP Laminate
The tensile stresses in FRP laminates on top and bottom of the retrofitted beam for different drop heights were shown in Figures 13 and Figures 14. As it is apparent, CFRP laminates due to their higher stiffness experience higher tensile stresses in comparison with AFRP laminates under the similar drop weight. It should be noted that since the drop weight was downward, the tensile stresses in bottom laminates has much higher values.

![Figure 13. Tensile Stress in Laminates for Repeated Drops (AFRP)](image)

![Figure 14. Tensile Stress in Laminates for Repeated Drops (CFRP)](image)

4.1.2.3 Damage index
The damage caused by the drop weight in FRP laminates are presented in Figure 15. Damage index is defined as the ratio of damaged area of the laminate to its original intact area. Therefore, this index may vary between 0 (intact) and 1 (destroyed). As one may see, damage
in the retrofitted beams by AFRP are in the range of 80% to 90% while in the retrofitted beams by CFRP has lower value between 15% and 60%.

Figure 15. Damage index in FRP laminates for Repeated Drops

(TB1-AFRP, TB2-CFRP)

5. Conclusions

By examining the behaviour of RC beams retrofitted using FRP laminates under impact load, following conclusion may be drawn:
- Finite element model accurately predict the behaviour of the retrofitted and unretrofitted beam.
- Comparing two types of composite laminates, CFRPs shows better effect on decreasing the midspan deflection.
- Comparing two types of composite laminates, AFRPs shows better effect on absorbing the impact energy.
- Increasing the length of FRP laminates has a positive effect on decreasing the deflection and the magnitude of stresses in concrete and FRP laminates under impact load.

6. References