Predicting the Behaviour of Reinforced Concrete Elements Strengthened with CFRP Using Model Updating Techniques

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ABSTRACT

War, terrorist attacks, explosions, progressive collapse and other unforeseen circumstances have damaged many buildings and bridges. Evidence from studying damaged structures has shown that Reinforced Concrete (RC) slabs, beams, columns, where damaged but not failed, can be strengthened using Carbon Fibre Reinforced Polymer (CFRP) to restore their load carrying capacities and make them serviceable. Currently there is no reliable analytical model that closely represents the true behaviour of the CFRP strengthened elements. This study extends the research on the implementation of model updating techniques on RC beams, to RC beams strengthened with CFRP. Our research shows that it is possible to find analytical models that closely match the experimental results. These analytical models can be used to more accurately predict the behaviour of the damaged structural elements strengthened with CFRP.

INTRODUCTION

There has been increasing media coverage reporting the severe damage or failure RC structures around the world due to various natural or manmade disasters.

Due to many uncertainties involved in modelling RC as a structural material, accurate modelling of RC structures is a complicated task. As a result of these uncertainties, a large number of physical samples are required to be tested in the laboratory to understand response of RC structural elements to applied loads. This makes this process very expensive.

The authors (Rafiq and Al-Farttoosi 2013) demonstrated that using model updating techniques is an effective way of finding suitable analytical models for RC beams that closely predicts their response to applied loading. This paper extends these findings to RC beams strengthened with CFRP.

The research question addressed in this paper therefore is: how to find a reliable analytical model that closely predicts the true behaviour of RC structural elements strengthened with CFRP? Answering this question will dramatically reduce the number of expensive laboratory tests and ultimately propose analytical models that can reliably assess the load carrying capacity of the damaged RC elements strengthened with CFRP.

To achieve this, model updating techniques (Brownjohn et al. 2001, Goulet et al. 2012) have been implemented within the IVCGA to tune some of the parameters of the FEA models to locate reliable analytical models that can result in acceptable matches with the experimental results.

LITERATURES SEARCH

According to the American Chemical Society (2003), the modern era of carbon fibres began in 1956. In 1958, Bacon demonstrated the use of the first high-performance carbon fibres. http://www.acs.org/content/dam/acsorg/education/whatischemistry/landmarks/carbonfibers/high-performance-carbon-fibers-commemorative-booklet.pdf (Accessed 9th September 2013). Bacon (1960) published his seminal paper in the Journal of Applied Physics on the use of carbon fibres.

According to Duthinh and Starnes (2004), the use of CFRP composites for the retrofitting of beams and slabs started around the late 1980s with the pioneering research at the Swiss Federal Laboratories for Materials Testing and Research or EMPA (Meier 1987). Recently, the use of Fibre Reinforced Polymer (FRP) for strengthening and upgrading of existing structural elements has gained particular attention (Hamed and Rabinovitch 2005). One reason that has attracted the construction industry towards using CFRP in the strengthening of existing structural elements is that it increases the stiffness and load carrying capacity of the RC elements. Addition of the CFRP delays the failure process and after the steel reinforcement yields, the beam can still carry increasing loads by the CFRP as the CFRP behaves elastically until failure occurs suddenly.

In the past few decades, a large number of laboratory experiments has been globally conducted due to the popularity of CFRP as a strengthening material. Esfahani et al. (2007) stated that a major challenge facing modern civil engineers is strengthening, upgrading and retrofitting of existing structures. They conducted a series of experiments to investigate the flexural behaviour of RC beams strengthened with the CFRP sheets. They also examined the effects of the reinforcing bar ratio on the these beams.

Recently several methods of externally strengthening CFRP techniques have been investigated. The most common technique used for strengthening and retrofitting RC structures is the externally bonded (EBR) technique. A major problem with the EBR technique is the CFRP debonding and concrete cover delamination. As a result of this, the EBR technique cannot resist the full tensile stress of the FRP material (Nguyen et al. 2001). Another technique proposed to limit the debonding effect is the Near Surface Mounted CFRP (NSM-CFRP), which is argued to increase both the flexure and shear strength of the RC member. The NSM-CFRP approach is based on bonding the CFRP laminate or strips in small grooves opened in the concrete cover (Al-Mahmoud 2010). ACI (2002) proposed another method for structure strengthening which is based on CFRP strips attached to the concrete by fasteners (MF-FRP)without any bonding.

Al-Saidy et al. (2010) investigated the structural performance of corroded RC beams repaired with CFRP sheets. Accelerated corrosion was used to induce corrosion in the beams. The result indicated that beams strengthened with CFRP sheet recovered their strength and their ultimate deflections were less than un-strengthened beams.

To assess the load carrying capacity of the CFRP strengthened elements, the use of FEA has been widely reported by the researchers. FEA results are commonly used for comparison of analytical and experimental results. Normally a trial and error method is employed to tune some of the FEA parameters in order to find an acceptable match. With the introduction of model updating, some of the uncertainties involved in this process have been addressed.

Mottershead and Friswell (1993) stated that FEA predictions are often called into question when they are in conflict with the laboratory test results. Model updating can be used to correct some parameters of the FEA models to be close to those from the tested structures. Mottershead and Friswell (1993) have also provided a review of the state of the art research on model updating techniques at that time. Amongst others, bridge structures have been the subject of a number of studies. Brownjohn et al. (2001) studied the sensitivity-analysis-based FEA model updating method and applied this to the condition assessment of bridges. Raphael and Smith (1998) used stochastic search as a reasoning system for complex diagnostic tasks in structural engineering. They proposed that the initial model set is created through model composition and that parameter values determined by stochastic search can lead to more accurate predictions of behaviour. Goulet et al. (2010) investigated multi-model structural performance monitoring that explicitly incorporated uncertainties and modelling assumptions in their research. This approach was applied to measurements from structural performance monitoring of the Langensand Bridge in Lucerne, Switzerland. They demonstrated that measurements from load tests may lead to numerical models that better reflect structural behaviour. In this approach they sampled thousands of models, starting with general parameterised FEA models. The population of selected candidate models was used to understand and predict behaviour, which leads to better structural management decision making. Numerical model updating techniques were used to predict the behaviour of masonry panels by Zhou (2002) and Rafiq et al. (2003). These authors introduced the concept of stiffness/strength corrector factors within the FEA which assigned different values of flexural rigidity or tensile strength to various zones within masonry wall panels.

TOOL AND TECHNIQUES

Model updating is an analytical technique that deals with the interpretation of measurement data from physical models tested in the laboratory or from testing/monitoring of existing structures. It identifies suitable analytical models that compare the measurement and analytical results. FEA is a universally accepted analytical tool that has the capability of modelling and analysing complex structures. Results obtained from the FEA model can be used to confidently simulate experimental results.

The Interactive Visualisation Clustering Genetic Algorithm System (IVCGA) developed by Packham et al. (Packham 2003; Packhan & Denham 2003) was designed to focus on user interaction from the outset. It allows exploration of specific regions of the solution space by 'zooming in' to selected regions, in order to evaluate the merit of solutions within these regions against specific requirements. The IVCGA uses genetic algorithms as its search tool and has a powerful visualisation interface that allows user interaction to explore various regions of the solution space and proposes alternative solution(s) that are the best fit for the intended purpose. This interface considerably enhances human-led exploration of the solution spaces. The interface allows automatic clustering which identifies clusters of design solutions relevant to various objectives of the problem. Colour is used to highlight important clusters, enhancing perceptual understanding of the data. Another powerful feature of the IVCGA is that it permits investigation of inter-relationships between design parameters and objectives.

Due to the inverse problem nature of the model updating process, a number of scenarios could result in similar results. Selection of a suitable solution from a large set of solutions that are a close match for the real structure is not an easy task and requires the expertise of professionals in the field. The authors' previous experience with using the IVCGA, for a variety of complex problems, has proven that the IVCGA allows easy interaction with the solution space to quickly single out superior solutions that are best fit for the purpose. This interaction may quickly lead in finding reliable solution(s) for the problem.

This paper uses the IVCGA to identify clusters of good solutions (FEA models) that result a good match with the experimental results. The user can then interact with the IVCGA to explore the suitability of solutions within these clusters and use their expert knowledge of the problem to select a suitable solution.

METHOD

FEA Model Description: Three RC beams strengthened with CFRP, tested by Esfahani et al. (2007), were used. The LUSAS finite element commercial package was used to conduct a non-linear analysis for all RC beams. In the modelling process, concrete was modelled as an 8 node 2-dimensional Plane Stress Continuum Element (QPM8). A nonlinear (Elastic: Isotropic, Plastic: Multi-Crack Concrete) Model 94 was used to model the concrete (LUSAS Manuals 2013). Steel reinforcement bars were modelled as Non-linear 2D-Bar elements with 3 nodes, using the Stress Potential von-Mises model that considers yield stress with hardening curve gradient properties. The CFRP was modelled as a 2-D bar element and a cohesive concrete model was used for the concrete–CFRP interface layer modelling. Load increments were used in the non-linear analysis process. Analysis was continued until the failure load was reached and load deflection graphs from the FEA results were generated for comparison with the experimental load deflection curves.

Model Updating Process using the IVCGA: The GA tool within the IVCGA was used to tune some of the analytical model parameters in order to find a suitable set of parameters that results in a good match with the physical model results. In this study, concrete elastic modulus (E-values) for each zone within the beam was selected to be the main variable of the GA. The reason for selecting this parameter was that the elastic modulus affects the stiffness and failure load of the RC beam. The beam was divided into 12 zones (Figure. 1) and each zone was assigned a different elastic modulus value; thus 12 variables were used in the GA optimization process. A binary string was selected. The main objective of the GA optimization process was to find a suitable set of concrete E-values that result in a good fit for the experiment load deflection curve.

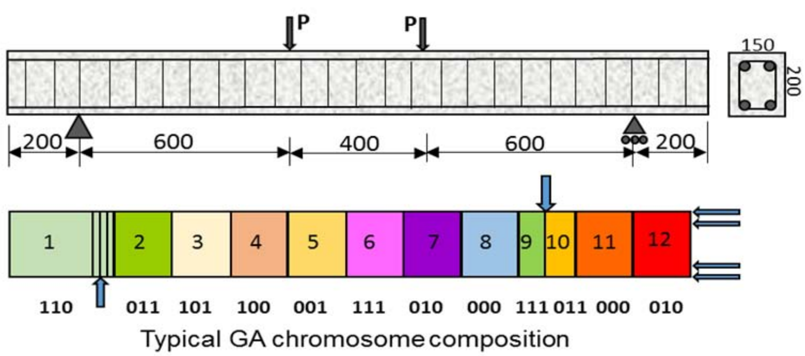

Figure 1. Division of RC beam into 12 zones

The following parameters were optimized in the objective function of the IVCGA:

1. Value of the failure load to be close to the experimental failure load. Failure load was defined as the load that causes failure of the concrete and the point at which the reinforced bars have reached their yield point. This value is determined from the experimental load deflection graph and compared with the analytical results. A typical load deflection curve for the RC beam with three distinct regions is shown in Figure 2.
2. Gradient of the load deflection curve to be close to the experimental gradient. It is worth mentioning that the RC load deflection graph (see Figure 2) has three distinct points.
   a. The point where the first crack in the concrete appears
   b. The point where the flexural cracks progress in the beam and the reinforcement starts to yield

c. The point where the beam totally collapses. This point is very difficult to capture in the FEA process. It is important to ensure that the overall deflected shape obtained by the FEA is close to the experimental results.

3. The value of the maximum deflection at the centre of the beam should be close to that of the experimental results.
4. A weighted sum of the above four objectives. In this process, various weightings were experimented based on the knowledge of previous work in this area and a trial and error process was used.

In this study the gradient of the line between the first crack and steel yield point is used in the optimization process.

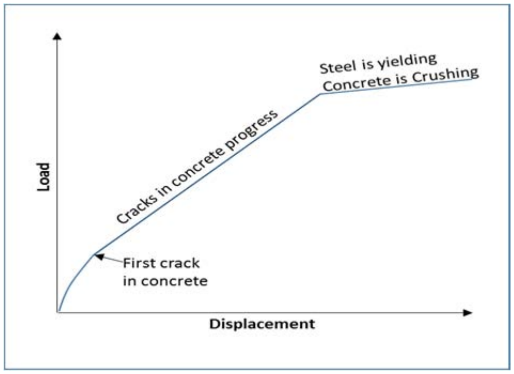

Figure 2. Typical Load Deflection Curve

In the optimization process, the IVCGA was first run for 120 generations and for a population of 100 individuals so a total 12000 solutions were generated. Unlike the normal GA process that only keeps the final population (100 solutions in this case), the IVCGA keeps all 12000 solutions generated throughout the optimization process to interactively be explored by the user.

The information generated by the IVCGA is organized in clusters of similar solution that can be visualized using different tools within the IVCGA. The user can zoom into regions of high performance solutions to conduct concentrated exploration of these selected regions in search of suitable solutions. Figure 3 shows an example of the interactive exploration process by the user.

In this example, each dot on the screen represents a solution and color represents clusters of similar solutions in which darker colours represent solution with better fit for a particular objective.

Once a preferred region of the solution space has been selected by the domain expert, further interactive exploration within this selected region can be conducted. As an example, the user may want to assess the suitability of selected solutions based on some specified criteria. For this specific problem, the user may wish to compare the experimental and the FEA load displacements for a selected solution. The user clicks on a selected solution using the computer mouse and the IVCGA interacts with the FEA software passing the data for that specific solution to the FEA and evaluates load deflection data for that specific solution. Figure 3 shows details of this process.

RESULTS

The IVCGA optimisation process results in 12 E-values for the concrete (one for each region of Figure. 1. Closer inspection revealed that the composition of these values follow the initiation of the crack pattern in the beam samples. Details of this process was discussed in Rafiq and Farttoosi (2013). An interesting finding of the

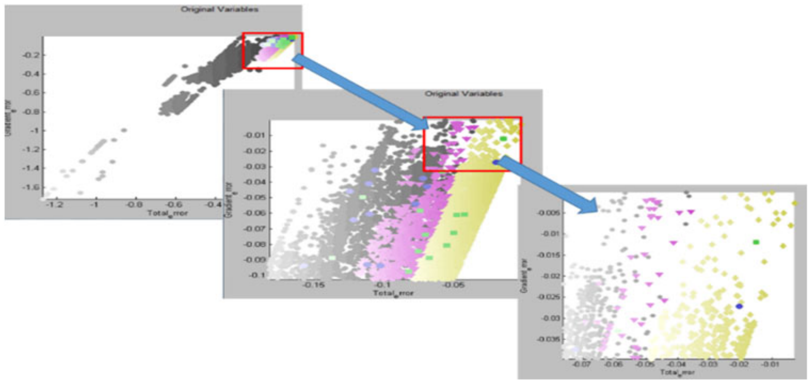

Figure. 3. The IVCGA interactive exploration of the solution space

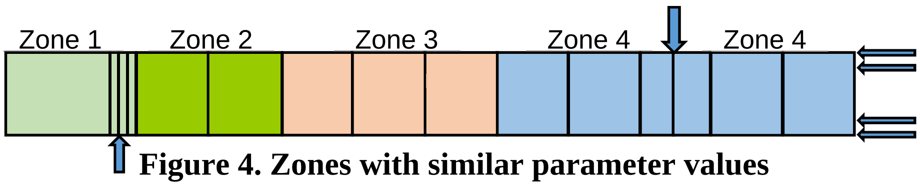

Figure 4. Zones with similar parameter values

model updating process for the beam with CFRP is that the CFRP delays the failure process of the samples. A consequence of this is propagation of initial cracks in beams with CFRP covers a wider area around the centre of the beam in comparison with the RC beams without the CFRP. The result of the rationalization process in shown in Figure 4. The four concrete E-values rationalised were then passed to the FEA to compare the experimental and the IVCGA load deflection plots.

The IVCGA Exploration of the Solution Space: The IVCGA is a powerful tool for the interactive exploration of the search and solution spaces. As mentioned before, the model updating process finds multiple solutions that could result in similar error. To increase confidence in the suitability of the selected solution, the IVCGA allows an interactive exploration of the solution space by the user. Figure 5 shows an example of such exploration.

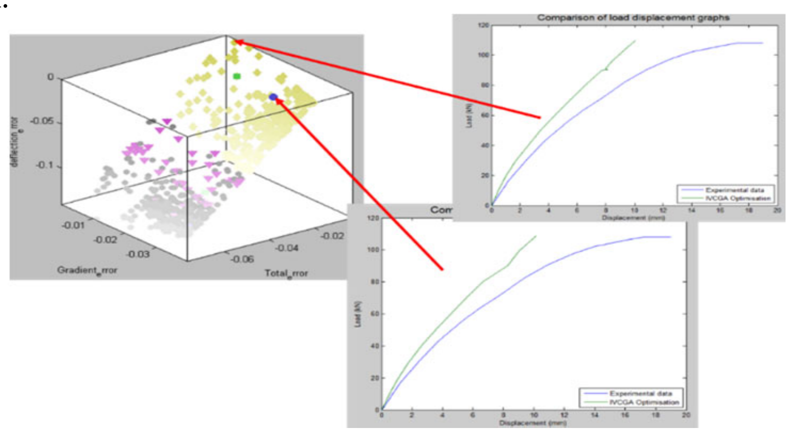

Figure 5. Interactively selecting a solution to assess it suitability

Although Figure 5 shows a good correlation between the FEA and the experiment results, the correlation is not as good as that of the same beam without the CFRP. The reason could be that in the FEA model a perfect bond is assumed between concrete and reinforcement bars. In the case of small diameter bars, this may be an acceptable assumption, but as the diameter of bars increase, the spacing between grips in the bars also increases, which subsequently increases the possibility of slip between steel bars and the surrounding concrete under excessive loads. This could explain the differences between experimental and the FEA results in the case of 20mm bars.

Validation process: The same tuned and rationalized values of the concrete elastic modulus values for the four zones of the reference beam (beam with 20 mm bars) and strengthened with CFRP (Esfahani et al. 2007) were then used in the FEA models of the RC beams with16 mm bars and 12 mm bars, to validate the suitability of the GA parameter tuning process.

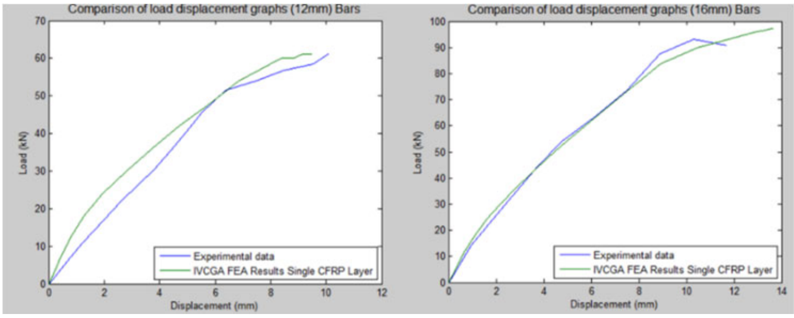

Figure 6. Extending the tuned E-values discovered by the IVCGA to 16mm and 12 mm bars

From Figure 6 it is clear that the correlation for both 16 and 12mm bars are very good. This demonstrates that the model selected through the IGCGA exploration process was a very good choice. This process demonstrated that with incorporating model-updating techniques with the ICVGA and with user interaction it was possible to find reliable analytical models that can closely predict the behaviour of physical models tested in the laboratory. Hence this has confidently answered the intended research question.

CONCLUSIONS

- Our investigation has confirmed that through the model updating process using the IVCGA it was possible to successfully find analytical models that results in a good match with the experimental results.
- The structural element stiffness is a dominating parameter that predominantly influences the shape of the load deflection curve. Structural element stiffness is mainly dependent on the material elastic moduli. Hence selection Concrete E-values as a subject of the optimisation process was a good choice.
- When the set of tuned concrete E-values, discovered by the IVCGA for 20mm bars, were used in beams with 16mm and 12mm bars, the FEA load deflection curves were a very good match with their experimental results. This proves the suitability and generality of the IVCGA selected model.

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