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Finite element modelling and testing of two-span concrete slab strips strengthened by externally-bonded composites and mechanical anchors

Jwan Alkhalil, Tamer El-Maaddawy *

Civil and Environmental Engineering, UAE University, P.O. Box 15551, Al Ain, United Arab Emirates

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ABSTRACT

Ten three-dimensional finite element (FE) models were developed in this paper to simulate the nonlinear behaviour of two-span reinforced concrete (RC) slab strips. Two slabs were unstrengthened and eight slabs were strengthened in either the sagging or the hogging region by externally-bonded carbon fiber-reinforced polymer (EB-CFRP) laminates with or without mechanical anchors. The tensile steel in the strengthened region was approximately 30% of that of the unstrengthened region to represent a continuous RC flexural element in need of strengthening. Laboratory tests were carried out to verify the accuracy and validity of the FE models. Each specimen had a total length of 3800 mm, a width of 400 mm and a depth of 125 mm. The provision of mechanical anchors in the hogging strengthening prevented the CFRP debonding mode of failure, slightly improved the strength gain, and significantly improved the slab ductility. Failure of the slab strips strengthened in the sagging regions was not dominated by CFRP debonding, and hence, the effect of including mechanical anchors in the sagging strengthening was concealed. Unstrengthened specimens exhibited significant deviations from the elastic response. Sagging strengthening decreased the deviation from the elastic response. Specimens strengthened in the hogging region exhibited insignificant moment redistribution ratios. The developed FE models captured the nonlinear behaviour of the tested slab strips with good accuracy. The inclusion of an interfacial bond stress-slip model in the analysis between the CFRP and the concrete had insignificant effect on the predicted response of strengthened specimens.

1. Introduction

Accidental omission of steel reinforcement at critical sections in continuous reinforced concrete (RC) slabs during construction would result in a severe safety hazard that requires immediate strengthening. Numerous studies demonstrated the effectiveness of using externally-bonded fiber-reinforced polymer (EB-FRP) laminates in strengthening of simply-supported RC structures [1–16]. In contrast, limited research has been carried out to investigate the nonlinear behaviour of continuous reinforced concrete (RC) structures strengthened in flexure with (EB-FRP) laminates [17–21]. Due to the lack of experimental evidences, most of the current design guidelines on the use of composites in strengthening do not allow moment redistribution in continuous RC structures strengthened with EB-FRP composites [23,24].

El-Refaie et al. [17] reported that although EB-FRP strengthening increased the strength of continuous RC beams, it resulted in a sudden peeling failure of the concrete cover adjacent to the FRP laminate accompanied by a reduction in ductility. Increasing the length of the EB-FRP laminates to cover the entire hogging or sagging regions could not prevent this mode of failure. Results indicated that there was an optimum number of CFRP layers beyond which no further strength gain was recorded. Oehlers et al. [18–19] studied the moment redistribution in continuous RC flexural members strengthened in the hogging region with either steel or FRP plates. Strengthened beams failed by debonding of FRP prior to concrete crushing. Based on theoretical analysis and limited experiments, it was concluded that substantial amounts of moment redistribution can occur in continuous plated beams. FRP-plated beams showed, however, limited ability to redistribute moments at their maximum strain compared with that of steel-plated beams. Akbarzadeh and Maghsoudi [20] investigated the behaviour of high strength concrete continuous beams strengthened with either carbon or glass fiber-reinforced polymer (CFRP or GFRP) laminates. The strengthening regime included transverse U-shaped CFRP-wraps installed near the ends of the longitudinal laminates. In all beams, the tensile steel reinforcements in the sagging and hogging regions were the same. Also, the beams were

* Corresponding author.
E-mail addresses: j.alkhalil@hotmail.com (J. Alkhalil), tamer.maaddawy@uaeu.ac.ae (T. El-Maaddawy).

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strengthened in both regions with the same amount of FRP reinforcement. Increasing the number of CFRP layers increased the strength gain but reduced the ductility and moment redistribution between the sagging and hogging regions due to a premature debonding of FRP reinforcement. Continuous beams strengthened with GFRP exhibited insignificant strength gain. The reduction in ductility and moment redistribution was less pronounced in the continuous beams strengthened with GFRP. The use of end-U-straps could not prevent an intermediate crack (IC) debonding mode of failure exhibited by strengthened beams. Aiello and Ombres [21] investigated the moment redistribution in two-span continuous beams strengthened with CFRP laminates. The beams had identical tensile steel reinforcement in the sagging and hogging regions. The strengthening regime included transverse U-wraps distributed along the length of the longitudinal FRP laminates. Failure of beams strengthened only in the sagging region involved debonding of the CFRP reinforcement along with detachment of the U-wrap from the beam's sides. Accordingly, doubling the number of CFRP laminates in the sagging region did not result in an additional increase the strength gain. Hogging strengthening with one CFRP laminate was not effective in improving the strength of the beams. The study by Aiello and Ombres [21] included development of a theoretical model to predict the structural response of FRP-strengthened continuous beams. Although the analytical predictions were generally in good agreement with experimental results, the adopted model was complicated and impractical.

Previous studies revealed that most of continuous RC elements strengthened with EB-FRP reinforcement exhibited undesirable sudden failure modes due to debonding of FRP or peeling-off of concrete cover. The sudden peeling mode of failure in strengthened specimens was not avoidable in some cases despite increasing the length of the CFRP laminate to cover the entire hogging or sagging zones or the use of U-wraps along the beam spans [17,21]. Sudden failure of the EB-FRP system would limit the moment redistribution between sagging and hogging regions. Further research into the performance of continuous RC elements strengthened with EB-FRP composites along with mechanical anchors (MA) is needed to minimize the risk of FRP debonding mode of failure.

If moment redistribution is to be relied on in the design of continuous RC structures, a rigorous analytical investigation should be conducted to ensure that the inelastic rotation capacity (available ductility) at the proposed plastic hinge location is in excess of the required plastic rotation (ductility demand). Published analytical models on the behaviour of continuous RC structures strengthened with EB-FRP were onerous from a computational viewpoint and difficult to use by practitioners [19,21]. In such cases, validated finite element (FE) models can serve as a powerful tool to simulate the nonlinear structural behaviour of strengthened continuous RC structural members including moment redistribution during all stages of loading until failure.

This paper contributes to an improved understanding of the nonlinear behaviour of two-span RC slab strips strengthened with EB-CFRP laminates. Ten three-dimensional FE models were developed to simulate the structural response of continuous RC slab strips strengthened with EB-CFRP laminates in either the sagging or the hogging region. The internal tensile steel in the strengthened region was approximately 30% of that of the unstrengthened region to resemble a continuous RC flexural element in need of strengthening. Laboratory tests were carried out to verify the accuracy and validity of the FE models. The effect of inclusion of MA in the strengthening regime on the structural response of strengthened specimens was investigated. The developed FE models simulated the nonlinear response of the tested slab strips with good accuracy. The models provided a valuable supplementary to the laboratory investigation by predicting strain data not captured experimentally in some specimens. The FE models validated in this study can be used as a numerical platform for performance prediction of continuous RC flexural elements strengthened with EB-FRP laminates.

2. Experimental investigation

2.1. Test matrix

The test matrix is given in Table 1. A total of ten RC slab strips were constructed and tested. The specimens were divided into two groups, five specimens each. Specimens of group [A] were deficient in the sagging regions whereas those of group [B] were deficient in the hogging region. The tensile steel in the deficient region was approximately 30% of that of the other region. This was done in an effort to resemble a flexural deficiency that might occur in field situations due to an error in design or an accidental omission of steel during construction. Specimens S-NS and H-NS, deficient in the sagging and hogging regions, respectively, were not strengthened to act as benchmarks. Test variables included the amount of EB composites used in strengthening (two and four EB-CFRP laminates) and the inclusion of MA in the strengthening regime. The strengthening regime in each counterpart specimens was not altered for the purpose of comparison (*i.e.* the behaviour of a specimen with a deficiency in the sagging region is compared with that of a counterpart specimen having the same deficiency and the same strengthening configuration but in the hogging region).

2.2. Test specimens

Geometry and details of steel reinforcement of test specimens are given in Fig. 1. The specimens had a width of 400 mm, a depth of 125 mm, and a total length of 3800 mm. Each span had a length of 1800 mm. The flexural steel reinforcement consisted of 2 No. 10 (10 mm diameter) deformed steel bars in the deficient region and 2 No. 10 + 3 No. 12 (12 mm diameter) steel bars in the nondeficient region. Minimal shear reinforcement in the form of 8 mm diameter stirrups were provided along the length of the specimens at a spacing of 75 mm to hold the steel cage. The clear cover was 25 mm. The stirrup spacing corresponded to approximately 0.87d, which is greater than the maximum limit of 0.5d specified by ACI 318 M-08 [24], where d = depth of the tensile steel reinforcement measured from the compression face of the specimen. This was done in an effort to minimize the effect of the presence of stirrups on the structural response of the specimens.

The specimens were subjected to two point loads located at the midspans and were tested to failure under monotonically increasing static loading. Load cells were used to record the total applied load and the middle support reaction. Two linear variable differential transducers (LVDTs) were used to record the midspan deflections. Strain gauges were bonded to the tensile steel reinforcing bars and EB-CFRP laminates at the midspans and over the middle support. A data logger was used to capture the readings.

2.3. Materials

The cube (150 × 150 mm) and cylinder (150 × 300 mm) compressive strengths of the concrete were 41 and 28 MPa, respectively, whereas the splitting tensile strength of the concrete was 2.6 MPa. The 10 and 12 mm diameter steel bars had measured yield strengths of 515 and 482 MPa and ultimate strengths of 667 and 590 MPa, respectively. The elongations at fracture were 18 and 20% for the 10 and 12 mm diameter bars, respectively. The EB composite system involved the use of flexible unidirectional carbon fiber fabrics impregnated and bonded to the concrete surface with