

A nonlinear finite element model for shear deficient heat-damaged concrete beams repaired using NSM CFRP strips



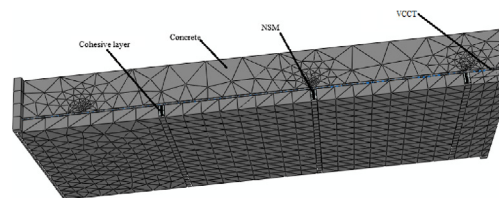
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HIGHLIGHTS

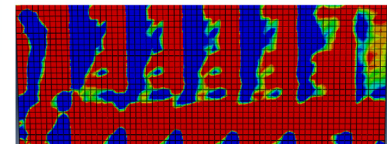
- NLFE modeling provided large data for modeling of NSM CFRP shear repaired beams.
- NLFE modeling described cover detachment sequence in NSM CFRP repaired beams.
- Understanding behavior of heat-damaged and NSM CFRP repaired beams.
- Recognizing effects of damage level and repair configuration upon beams' behavior.

GRAPHICAL ABSTRACT



Mesh configuration of heat-damaged and shear-deficient beams repaired using near surface mounted (NSM) CFRP strip.

Shearing stress trajectories between heat-damaged concrete and NSM CFRP strips under variable transverse loadings.



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ABSTRACT

The mechanical performance of heat-damaged and shear-deficient beams, retrofitted using near surface mounted (NSM) CFRP strips, was investigated using nonlinear finite element (NLFE) modeling. This was carried out using the software ABAQUS with the cohesive element and the virtual crack closure technique (VCCT) implemented to model bond interface between concrete and NSM CFRP strips and concrete cover separation, respectively. The NLFE model was validated using experimental data from tests on shear-deficient and heat-damaged beams before predictions expanded to consider wide spectrum of exposure temperatures in the range of 23–700 °C and varying spacing between vertical NSM CFRP strips (75–200 mm). NLFE predictions of mechanical response and cracking and failure modes for intact, heat-damaged, retrofitted and strengthened beams were in an excellent agreement with experimentally obtained results. The study revealed that the retrofitting efficiency hence benefit was higher for beams, exposed to temperatures below 600 °C and repaired using NSM CFRP strips at spacing greater than 75 mm. In general, concrete beams, exposed to 400 °C and greater then repaired for shear, tended to fail by concrete cover separation; especially when NSM CFRP strips were inserted at spacing values of 100 mm and less; others experienced dominant typical shear failure. Finally, the present NLFE model explained failure mechanism of NSM CFRP shear-strengthened beams through concrete cover separation.

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1. Introduction

Retrofitting of deteriorated concrete members using Fiber Reinforced Polymer (FRP) aimed at boosting their load capacity and

preserving their durability and volume stability. Both externally bonded FRP reinforcement (EBR FRP) in the form of plates or sheets and near-surface mounted (NSM) FRP composites, adhered inside man-made grooves within the concrete cover, were employed for this purpose [1–3]. Field and experimental experience indicated that optimal utilization of EBR FRP in repairing flexural elements or beam-column joints was never achieved due to the composites'

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premature detachment from concrete [3,4]. Furthermore, the vulnerability of EBR FRP composites to sun, moisture and fire limited further their potential use in repairing field structures; especially those located in aggressive environments [3–8].

NSM FRP strips were recently suggested as an alternative to EBR FRP laminates because of their improved bond with concrete and better resistance against environmental attack and fire. Recently, several studies were undertaken to investigate flexural and shear behaviors of concrete beams, strengthened with NSM FRP bars or strips [9–17]. Results revealed that NSM FRP strips were more effective and practical than EBR FRP composites in boosting shear and flexural deficient beams. Generally, reinforced concrete (RC) beams, strengthened/repared with NSM FRP strips tended to fail through concrete cover peeling-off at steel location [16–19]. Key parameters such as embedment length, and stiffness of NSM CFRP strips, as well as spacing between NSM CFRP strips, concrete's cracking status, and tensile strength were found to shape flexural and shear performances of NSM CFRP retrofitted beams [20].

To understand the impact of the above key parameters upon the performance of beams, retrofitted with CFRP composites, time and effort consuming experimental testing programs would be needed. As an alternative, nonlinear finite element (NLFE) modeling has been utilized to generate sizable amount of data for varying cases of repair in a shorter period and at a lower cost [21–28].

Alkhalil and El-Maaddawy [21] used 2D NLFE models to predict the behavior of two-span concrete slabs strengthened by externally-bonded composites and mechanical anchors then validated their results experimentally. Others developed 3D NLFE models that can accurately simulate the response and performance of RC beams, externally strengthened with short-length CFRP plates [22]. These models were capable of predicting capacity and capturing debonding failure mode of FRP strengthened beams. In another study, Nistico et al. [23] employed microplane-based NLFE approach for modeling shear-strengthened concrete beams using full wraps of CFRP sheets. Predictions were in an excellent agreement with experimental data, obtained by the same authors. Others modeled the torsional behavior of concrete beams, strengthened with full wraps of CFRP sheets, using NLFE [24]. An improved softened membrane model for torsion (SMMT FRP), that considered the influence of FRP composites on the compressive behavior of cracked concrete, was proposed. Parameters such as post-cracking stiffness, peak torque and peak twist were accurately captured by the improved SMMT FRP [24].

It is fundamental in NLFE modeling of reinforced concrete beams, damaged by an external physical or chemical attack then repaired using CFRP composites, to account for materials' nonlinearities and presence of cracking [25–28]. Jadooe and others used NLFE to model flexural behavior of concrete beams, heated under ISO-834 standard fire to 600 or 700 °C and then repaired with NSM CFRP strips to recover their mechanical characteristics [25]. Likewise, Firmo et al. used 3D NLFE modeling to simulate post-fire behavior of reinforced concrete beams; strengthened at their tension side with EBR FRP or NSM CFRP strips then fire proofed using a relatively thick mortar layer [26]. They took into account temperature-dependent thermo-physical and mechanical properties of the constituent materials and CFRP-concrete interaction utilizing bi-linear bond-slip relationships, previously calibrated for different temperatures. In another work, NLFE modeling was implemented to predict the performance of concrete beams, damaged under a temperature of 500 °C then repaired for shear with EBR CFRP strips at different inclination and spacing values [27]. In another study, shear-deficient, sulfate-damaged and CFRP repaired beams were modeled using NLFE method before validated using experimental data [28]. Prediction were then expanded to predict the contribution of U-shaped CFRP sheets, positioned at varying spacing and inclination, in regaining structural performance and controlling failure of sulfate-damaged

beams. Most studies assumed perfect bond between CFRP composites and concrete, while few others accounted for possible slippage between CFRP composites and concrete using spring elements but none simulated the delamination tendency of concrete at steel level; whenever that was applicable [21–28].

The behavior of NSM CFRP strengthened concrete structures has been simulated using 2D and 3D NLFE models [29–31]. Researchers either assumed a perfect bond between NSM CFRP and concrete [29] or utilized fine mesh and spring elements to account for possible debonding between NSM CFRP [30,31]. Such elements simulated crack open mode failure only which is not representative of actual crack initiation and propagation behavior in NSM CFRP repaired beams [30,31]. Furthermore, none of the published literature works accounted for concrete delamination at the level of steel reinforcement in their modeling [29–31].

2. Problem statement, objectives, and scope

Several empirical models were developed to predict strain in NSM CFRP strips, used for flexural retrofitting of concrete beams [18–20]. This aided in evaluating repair potential and enabled analytical computation of mechanical performance. Unfortunately, similar models are not available to predict ultimate strain in CFRP NSM strips, used as additional shear reinforcement; due to lack of literature data. NLFE modeling could generate needed data and determine critical key parameters upon the mechanical performance of beams, strengthened for shear deficiency using NSM CFRP strips. Furthermore, NLFE stress trajectories could explain the mechanism of concrete cover peeling-off in the latter concrete beams. Accordingly, such undesirable failure mode could be prevented or delayed through the use of proper repair measures such as implantation of steel dowels across concrete cover.

Considering nonlinearity in behavior of concrete and reinforcing steel, horizontal cracking in concrete cover at reinforcing steel level and bond behavior between either NSM CFRP or steel reinforcement and concrete in NLFE modeling would be essential to precisely describe failure mechanisms and quantify mechanical response of NSM CFRP repaired beams; especially concrete cover peeling-off. Those were indeed incorporated in the present NLFE model, proposed and implemented using ABAQUS software to predict the performance of heat-damaged and shear-deficient concrete beams, repaired using NSM CFRP strips as external shear stirrups [32]. The NLFE model was validated using experimentally published data before its predictions extended to consider pre-repair exposure temperature (23–700 °C) and horizontal spacing between NSM CFRP strips (75–200 mm). Mechanical characteristics, and strain at failure in critical NSM CFRP strip were obtained whereas cracking modes mapped to understand and determine failure mechanism for different strengthened/repared beams.

3. Experimental work: an overview

The NLFE model presented in this work was validated using the results from the experimental work, published by Haddad and Almasaeid [16]. Reinforced concrete beams (150 × 250 × 1400 mm) were designed with insufficient shear reinforcement, cast using ordinary strength concrete of a matured strength of 47 MPa, exposed to high temperatures in the range of 300–600 °C, and shear strengthened using NSM-CFRP then tested under four-point loading. Fig. 1 illustrates geometric dimensions and distribution of internal and external reinforcements in these beams along with loading configuration, as applied at testing. The mechanical properties of concrete and steel under different temperatures are summarized in Table 1. The RC beams were divided into four sets with I and II corresponded to control and heat-treated, whereas III and IV corresponded to intact/strengthened and heat-damaged/

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