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Finite Element Modeling of Shear Deficient Beams Bonded with Aluminum Plates

A. Abu-Obeidah, R. Hawileh and J.A. Abdalla
Department of Civil Engineering
American University of Sharjah, United Arab Emirates

Abstract

This paper presents the development of a three-dimensional nonlinear finite element (FE) model to capture and predict the response of a shear deficient simply supported reinforced concrete (RC) beam strengthened externally with aluminum alloy plates. Two FE models were developed based on experimental tests conducted by the authors in a previous investigation. The models developed have exact geometry and boundary conditions to that of the experimental specimens. The predicted FE results for the load-midspan deflection are compared to the measured experimental data. Close agreement was found between the predicted and measured results at all stages of loading for both models developed.

Keywords: nonlinear analysis; aluminum alloy; reinforced concrete; shear deficient; ANSYS; finite element method, strengthening.

1 Introduction

Deterioration of existing reinforced concrete (RC) structures such as buildings and bridges with time due to several environmental effects and design codes upgrades [1,2] warrants strengthening structural members in flexure and shear. In the United States and Japan, many constructed concrete structures do not meet the upgraded seismic design codes regarding shear capacity and ductility [1] which leads to tremendous damages. For example, Hyogoken–Nanbu Earthquake that occurred in 1995 caused severe damages in many concrete piers and rigid frames that were used as highways because they were constructed based on the 1980 design codes [1]. As a result, such structures need to be strengthened using simple, effective and economical materials. The existing methods for strengthening concrete structures nowadays are either by using steel plates or fiber reinforced polymer (FRP) plates or sheets. These materials were used widely in external strengthening of RC elements in shear and flexure and proved their effectiveness in increasing load carrying capacity and ductility of many structural elements. However, there are some disadvantages of using FRP and steel as the strengthening materials of choice that many researchers are trying to overcome by using other materials. Some of the disadvantages of the FRP materials are their use limitation because of their unidirectional properties, their low thermal resistance, and their orthotropic and brittle behavior. In addition, the steel disadvantages are the low corrosion resistance and the need of painting and coating.

Other metals such as Aluminum alloy plates, overcome the disadvantages of the FRP and steel materials. Aluminum as a metal has many effective structural properties such as being isotropic, highly ductile, a good thermal and corrosion resistance, and high strength to weight ratio [3].

Abdalla et al. [3]conducted a research investigation on strengthening RC beams in shear with externally bonded aluminum plates attached perpendicular to the longitudinal side of the beam and another specimen bonded with a 10 mm x 790 mm aluminum alloy plate bonded diagonally at an angle of ±10°. In addition, an unstrengthened beam was tested to serve as a control beam. The tested specimens showed an increase in the load carrying capacity of up to 80% along with increase in the deflection at yield and ultimate. It was concluded that aluminum alloys plates can used to externally strengthen RC beams in shear. In this study, a shear deficient beam strengthened with five Aluminum plates bonded on a 45^{o} from the longitudinal side of the beam is added to the work matrix. The test for the three beams was conducted on 1840 mm long beam models under four-point flexural bending test.

The aim of this paper is to numerically develop a finite element (FE) model that can predict the performance of RC beams strengthened with Aluminum plates. Two FE models are developed using the finite element software, ANSYS [4]. The models consider the different material constitutive laws for the concrete in tension (cracking) and compression, and yielding of the aluminum plates and steel reinforcements. The model is validated by comparing the predicted load-deflection response results with the measured experimental data conducted earlier by the authors [3]. FE modeling could serve as a numerical platform for predicting the behavior of RC beams externally strengthened in shear with aluminum plates.

2 Finite element model development

Figure 1 shows the cross-section, detailing and loading of the tested simply supported RC beam specimens. The two beams were 1840 mm long having a rectangular cross-section, 150 mm wide and 250 mm deep. The beams were heavily reinforced in flexural by two 16 mm diameter reinforcement to force shear failure to occur. The beam specimens were tested in four-point bending monotonically up to failure. The clear span of the tested RC beams was 1690 mm and the two loading points were 563.33 mm apart located symmetrically about the beam's mid-span. The main flexural steel reinforcement was two #16 mm diameter steel reinforcement bars.

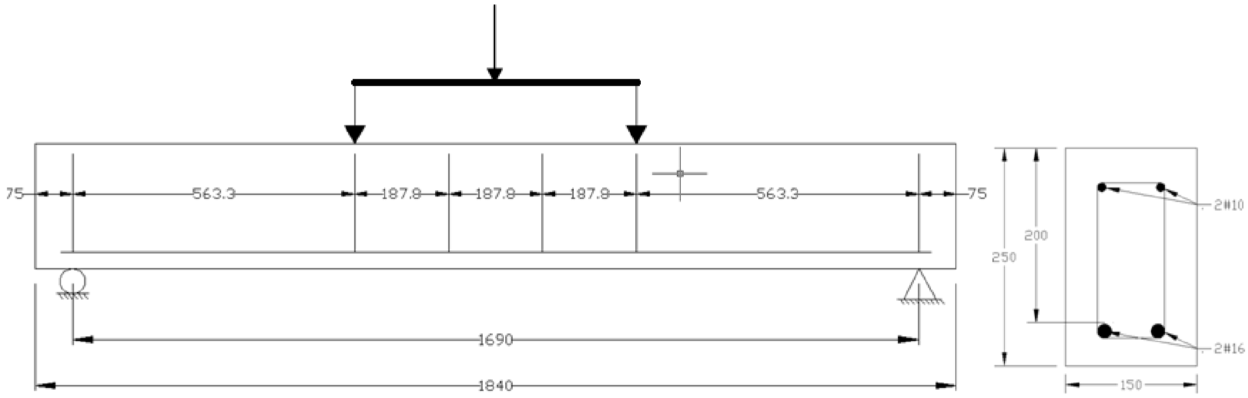


Figure 1: Control Beam (CB)

Figure 2 shows the strengthening scheme of the second beam "AL90" that was externally strengthened in shear with 2 mm thick aluminum alloy plates, attached using epoxy adhesive. The plates were 5 mm wide and 240 mm deep. The beam was strengthened with five aluminum plates spaced at 130 mm, center to center, located in the shear spans of the beam and oriented perpendicular to the longitudinal axis of the beam as shown in Figure 2.

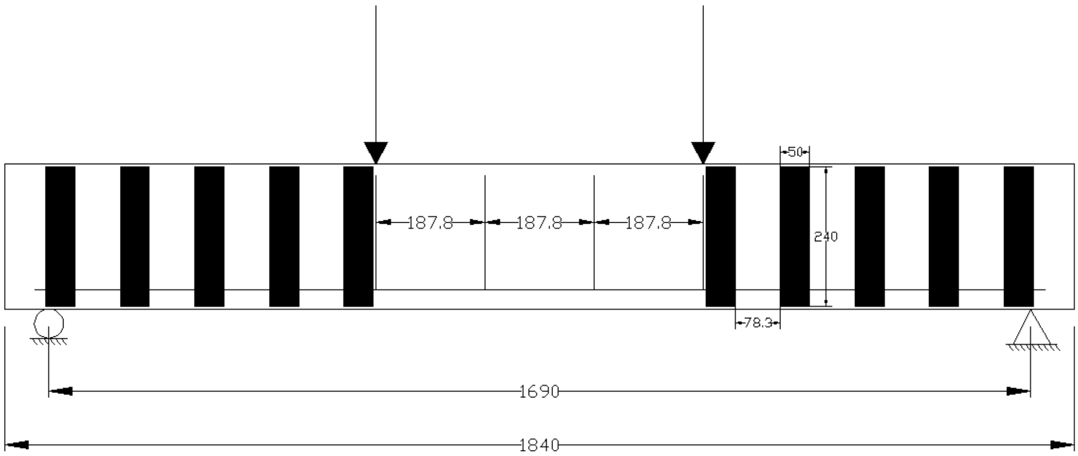
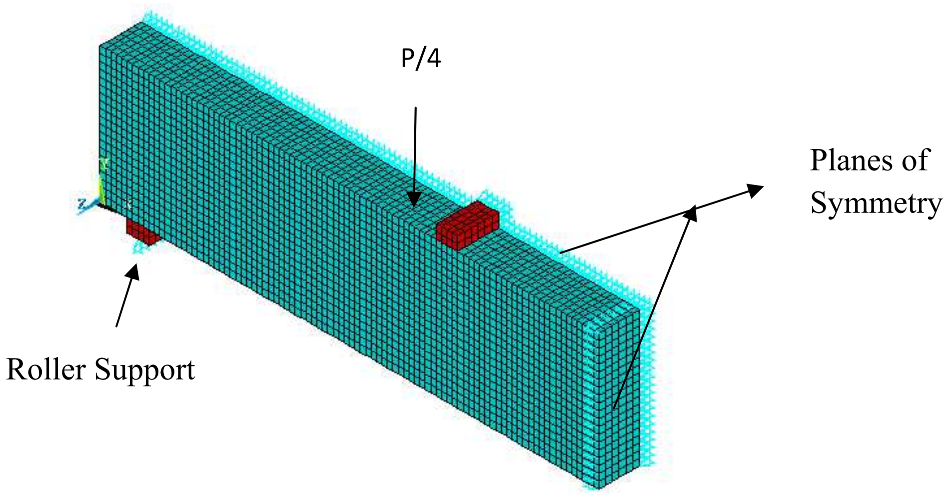
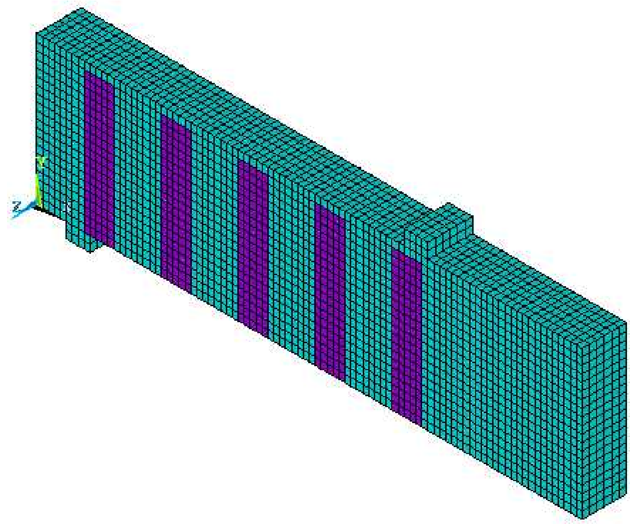


Figure 2: Strengthened Beam with Aluminum Alloy Plates (AL90)

Due to symmetry in the geometry, material properties, loading, and boundary conditions, a quarter FE model was modeled and simulated in the finite element software, ANSYS [4]. Figure 3 shows the developed FE models for the control and strengthened specimens. It is clear from Figure 3 (a) that the developed model has two planes of symmetries in the longitudinal and transverse directions of the beam specimen. Symmetry is simulated by restraining the deformation perpendicular to the plane of symmetry via roller supports. Simulating a quarter model of the beam will reduce the total number of elements and thus reduce the computational time.



(a). Control Beam (CB)



(b). Strengthened Specimen (AL90)

Figure 3: Developed FE Models

Multiple element types were used to model the three beams. SOLID65 [4] elements are used to model the concrete material. SOLID65 has a total of 8 nodes with three translational degrees of freedom in the x, y, and z directions at each node. SOLID65 has the ability of simulating the nonlinear behavior of concrete by cracking in tension and crushing in compression. The steel bars reinforcements are modeled using LINK8 [1] elements. LINK8 is a uniaxial tension-compression 3-D spar element defined with three degrees of freedom at each node. The element is capable of simulating plasticity, creep, stress stiffening, and large deflection effects. The aluminum plates are modeled using SHELL63 [4] elements. SHELL63 has six degrees of freedom at each node; translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. The loading and steel rollers were simulated as rigid supports using SOLID45 [4] elements to avoid stress concentrations at the surfaces of the concrete beam. In these models, it is assumed that there is a perfect bond between the concrete and steel bars and between the aluminum plates and adjacent concrete surfaces.

The mechanical material properties and constitutive laws are assigned to the different material components of the beam specimens. The modulus of elasticity, compressive strength, and Poisson's ratio of the concrete material is taken as 28.7 GPa, 37.5 MPa, and 0.2, respectively. The nonlinear behavior of the concrete material in compression was modeled using the Hognestad model [5] Cracking of the concrete elements was simulated using the William and Warnke [6] model that is employed in the concrete constitutive material model in ANSYS [4]. The tensile strength of concrete is taken as $0.62\sqrt{f'_c}$, where f'_c is the compressive strength of concrete. The concrete model also requires values for the open and close shear coefficients, β_t and β_c, which typically range from 0.0 and 1.0. In this study, values of 0.1 and 0.2 are used for β_t *and* β_c, respectively.

The modulus of elasticity and yield strength of the flexural reinforcement as measured experimentally are 199 GPa and 590 MPa, respectively. The Poisson's ratio for the steel reinforcement is assumed to be 0.3. The nonlinear material property of the steel material was assumed to be elastic-perfectly plastic. The aluminum mechanical properties are also measured experimentally. The obtained modulus of elasticity, yield strength, tensile strength, and strain at break are 72 GPa, 145 MPa, 295 MPa, and 22%, respectively. The Poisson's ratio for the steel reinforcement is assumed to be 0.33.The nonlinear response of the aluminum plates is assumed to be elastic-fully plastic. The Von-Misses failure criterion is used to define yielding of the aluminum plates and steel reinforcement. In the experimental program, Sikadur 30 LP is used to bond the aluminum plates to the concrete surfaces. The Sikadur 30 LP has a modulus of elasticity of 10 GPA and a tensile strength of 30 MPa.

3 Results and discussion

The validation of the FE models was conducted by comparing the predicted load-midspan deflection results and failure load with that of the measured experimental data. Table 1 shows a comparison between the numerical and experimental load carrying capacity and the corresponding ultimate midspan deflection for the tested beam specimens. Furthermore, Figures 4 and 5 show the predicted and measured load-midspan deflection response for the "CB" and "Al90" beam specimens, respectively.

Specimen	Load (KN) Exp	FE	%Difference	Ultimate Deflection (mm) Exp	FE	% Difference
CB	60.73	61.00	0.44	4.42	4.11	-7.04
Al90	106.64	107.00	0.34	7.15	7.15	0.00

Table 1: Comparison between the predicted and measured results

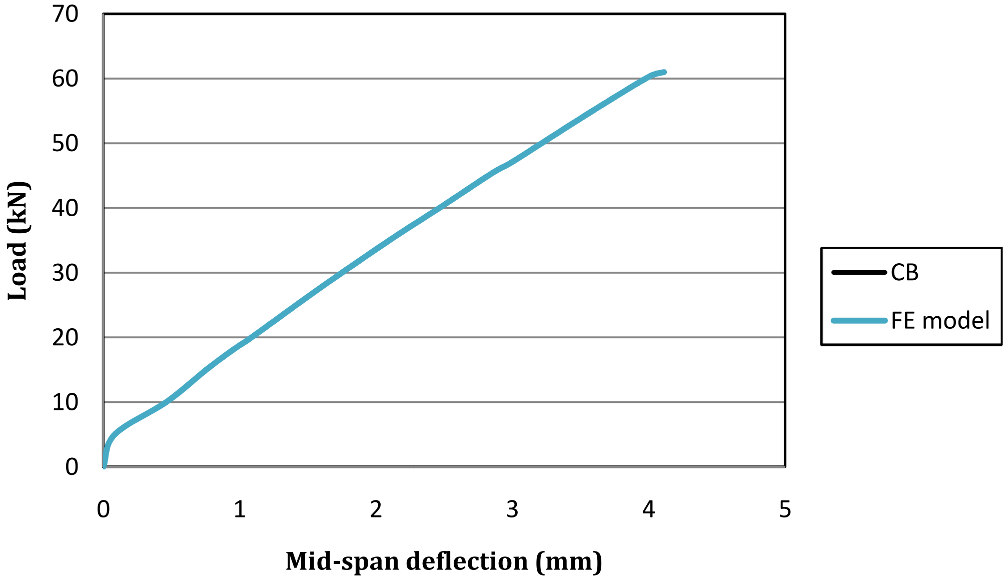


Figure 4: Load versus midspan deflection for the CB specimen

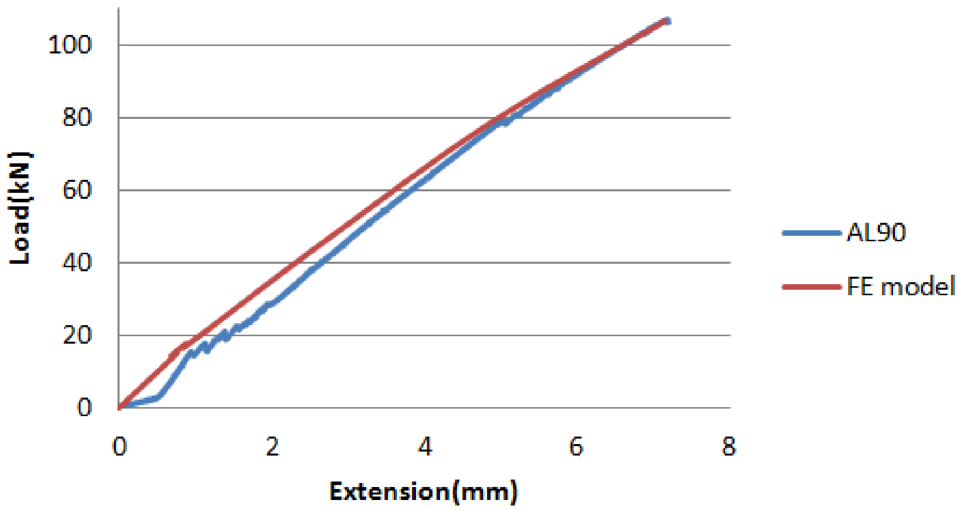


Figure 5: Load versus midspan deflection for the "AL90" specimen

It is clear from Figures 4 and 5 and Table 1 that there is a good agreement between the experimental and predicted FE results at all stages of loading till failure of the specimens. The developed FE models slightly overestimate the load carrying capacity and underestimate the ultimate deflection as depicted in Table 1. As a result, it could be concluded that the developed FE models are valid and reliable to investigate the behavior of RC beams externally strengthened in shear with aluminum plates.

4 Summary and Conclusions

Two-3D nonlinear FE models were developed in this study to simulate the response of RC beams strengthened in shear with aluminum plates. The models are validated by comparing the predicted FE results with the measured experimental data conducted by the authors in a previous research investigation. Based on the results of this study, the following conclusion could be drawn:

- The load-deflection response of the FE models is in a good agreement with the measured experimental data.
- The developed FE models slightly overestimate the load carrying capacity and underestimate the ultimate deflection.
- The developed and validated FE models presented in this study could serve as a numerical platform and alternative to the expensive and time consuming experimental testing to investigate the behavior and predict the performance of RC beams externally strengthened in shear with aluminum plates.

The authors will develop further models and perform various parametric studies in a future research to investigate the effect of several parameters such as plate spacing, thickness, width, and orientation on the performance of RC beams strengthened in shear with the innovative aluminum alloy plates.

Acknowledgment

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