



The Use of Sustainable Materials for Quick Repair of Aging Bridges

Phase II Final Report

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EXECUTIVE SUMMARY

During the last decade fiber reinforced polymer (FRP) materials have gained wide acceptance for repair and strengthening of existing infrastructures or to design new infrastructures due to their desirable properties (high strength to weight ratio, light weight and consequent ease of field placement, corrosion resistance, durability, and low maintenance cost among others). There is a need to strengthen the deficient and aging civil infrastructure or new structures that are identified with certain design flaws against sudden loads including impact, blast, natural disasters, or increased traffic loads over time. The addition of FRP materials to upgrade the deficiencies or to strengthen the structural components prior to collapse can save lives and damage to the infrastructure, and reduces the need for their costly replacement. Furthermore, due to their desirable properties, the retrofit with the FRP materials provides an excellent replacement for traditional materials including steel jacket to strengthen the damaged reinforced concrete structural members that are repairable.

An innovative, reliable, fast, durable, and cost efficient FRP retrofit technique was proposed to enhance the capacity of bridge components that are in serious need of strengthening due to deterioration, accidental damage, or an increase in axial load demand. The strengthening technique involved the use of FRP sheets to wrap the column as an external reinforcement. Nonlinear finite element analysis (FEA) software program was used to simulate the behavior of scaled-down concrete bridge column models prior and after fiber composite wrapping retrofit. The as-built and FRP-retrofitted columns were compared to assess the confinement effectiveness of the retrofit technique necessary to overcome the increase demand in axial load capacity. The FRP-strengthened column showed considerable improvement in axial load and displacement capacities as compared to as-built column model. The findings reveal that the FRP strengthening can be used to restore the original strength of the column that might have been lost due to possible deterioration, and even to carry the increased traffic load that was never designed for. Such solution can postpone the costly replacement of the bridge or bridge components while insuring the safety of the structure. Additionally, the use of fiber reinforced polymers offers an excellent alternative rehabilitation technique as non-metallic sustainable reinforcement with considerable savings relative to conventional strengthening methods due to the low maintenance and life cycle costs.

INTRODUCTION

Fiber reinforced polymer (FRP) wrapping of concrete columns is an ideal technique to increase the strength and ductility of these structural elements (Rochette and Labossiere, 2000; Parvin and Jamwal, 2006; Ozbakkaloglu and Akin, 2011). In this project, the performance of scaled-down as-built and FRP-wrapped circular concrete columns have been investigated using ANSYS nonlinear finite element analysis software program at Ohio Supercomputer Center (ANSYS 2009) to gain insight into the behavior of such columns.

METHODOLOGY

In the following sections the finite element analysis modeling details including the geometry and reinforcement arrangement of reinforced concrete (RC) column and carbon fiber reinforced polymer (CFRP)-wrapped RC column, element types, material models, boundary conditions, and simulation results are discussed.

Geometry and Reinforcement Details

In order to examine the behavior of axially loaded column before and after CFRP-strengthening, scaled-down finite element models of circular tied columns were developed. The columns had the dimension of 152 mm \times 760 mm. The geometry and reinforcement detail of the finite element model of the column is shown in Fig. 1. The bottom of the concrete columns was fixed. The axial load was increased incrementally and applied to the top cross-section of the column on the steel plate. Figs 2 and 3 show the load and support conditions of the finite element column models in X-Z and Y-Z directions, respectively, where Z axis is along the axial direction and X and Y axes are in the plane perpendicular to axial direction of the column. Compression strength of 28.6 MPa was assigned for the concrete. The longitudinal steel bars and ties had yield strengths of 483 MPa, and 400 MPa, respectively. Two layers of Tyfo@SCH-41 CFRP sheet with 0° and 90° fiber orientations with respect to the hoop direction were applied to the CFRP-

strengthened column. Although the column in this case is under pure axial load, the fiber orientations were selected such that the column would be able to withstand axial and flexural deformations for other loading scenarios. In accordance with the manufacturer's data sheet, Tyfo®SCH-41 sheet has a 1 mm thickness per layer with a tensile strength of 986 MPa in the fiber direction, tensile modulus of 95.8 GPa, and rupture strain of 1%.

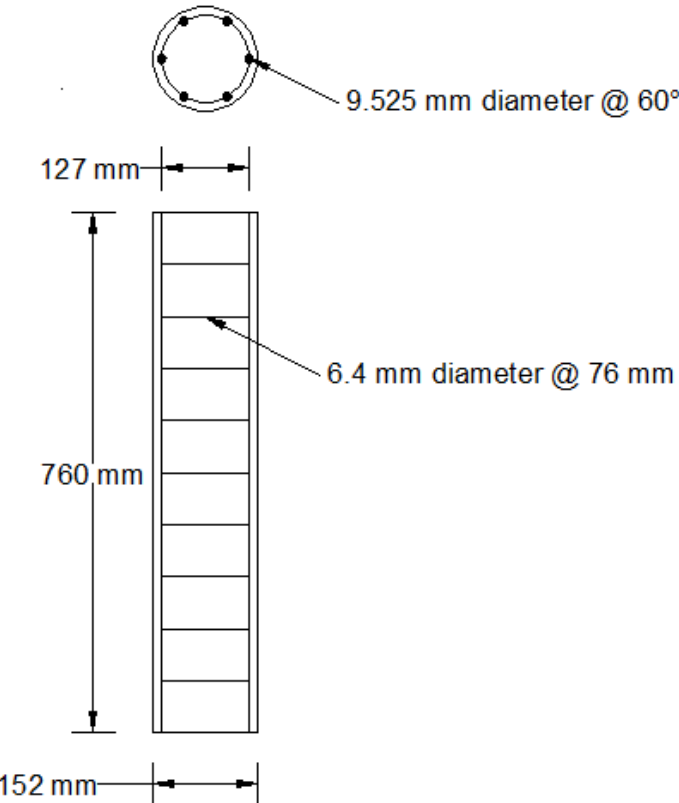


Fig. 1. Geometry and reinforcement details of FEA column models

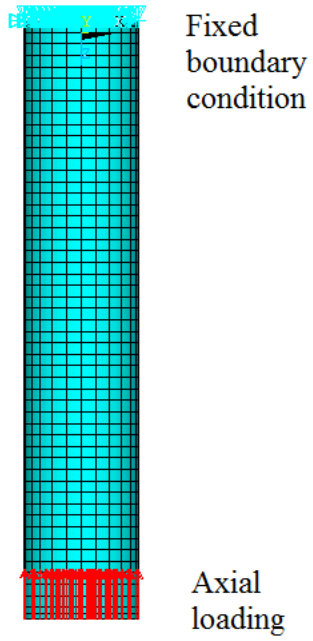


Fig. 2. X-Z view of applied axial load and fixed boundary conditions of FEA column models

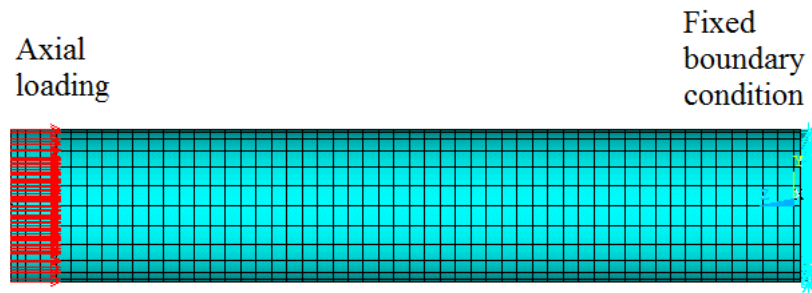


Fig. 3. Y-Z view of applied axial load and fixed boundary conditions of FEA column models

Element Types

To model the concrete, “Solid65” which is a three-dimensional reinforced concrete element with the ability to crack in tension and crush in compression and options for large plastic deformation, nonlinear material property, and element death and birth attributes was selected. The element has eight nodes with three nodal translational degrees of freedom.

The reinforcement bars were modeled by “Link180”, a three-dimensional spar element, which is a two-node uniaxial tension-compression element with three nodal degrees of freedom and options for plasticity, creep, swelling, element death and birth, stress stiffening, and large deflection capabilities. In this study, plasticity and element death and birth options were implemented.

Carbon fiber reinforced polymer (CFRP) sheets were modeled using “Shell181”, a finite strain shell element, suitable to model thin to moderately thick shell structures with a membrane option. Again, this element has features of plasticity, stress stiffening, large deflection, birth and death, and nonlinear stabilization. Shell181 element is a four-node element possessing six nodal translational degrees of freedom with the membrane option.

Material Models

Drucker-Prager material model was employed for the concrete. The selected values of cohesion, angle of internal friction, and dilatancy angle were 8.275 MPa, 28°, and, 0°, respectively. 0°dilatancy angle would result in no increase in material volume when yielding and the flow is non-associative. The material model replicates core concrete confinement effect.

The reinforcement bars were modeled as an elastic-perfectly plastic material identical in tension and compression. Perfect bond assumption between the steel bars and concrete was prescribed by connecting Link180 steel bar element nodes with adjacent Solid65 concrete nodes so that the two materials share the same nodes.

The CFRP composite was characterized as an orthotropic material model with option to designate the fiber layer orientation. Perfect bond assumption between the CFRP sheets and concrete was implemented by connecting adjacent nodes of Shell181 and Solid65 element to share the same nodes.

Mesh Generation and Boundary Conditions

A preliminary finite element analysis was performed on the control column model by varying the mesh size from course to fine. By comparing preliminary axial force versus displacement results, a workable mesh density with 15.2 mm element size was selected. To achieve even stress distributions and to avoid stress concentration, steel plates with 152 mm diameter and 15 mm thickness were added at the locations of loading and support of the columns. Three-dimensional Solid185 element was used to model the steel plates. Free and fixed boundary conditions were applied to the top and bottom end of the columns, respectively.

Nonlinear Solutions and Failure Criterion

The total load was applied as series of load steps. Newton Raphson method option in ANSYS was employed to fulfill the convergence at the end of each load increment within the tolerance convergence norms. Based on the response of the column for the previous load increment, the minimum and maximum load increments were controlled and predicted by ANSYS automatic load stepping. With cracking of the concrete, yielding of the steel bar reinforcement, and post peak phases, a gradual small load increment was applied to capture the stiffness degradation due to the crack propagation. Failure of FEA column model was predicted when the analysis stopped to converge for 0.001 kN load increment using APDL loading code.

Finite Element Analysis Results of As-Built and CFRP-Strengthened RC Concrete Columns

In the finite element analysis results, displacement values were obtained from the center node at the top of the column. Fig. 4 shows the axial force versus displacement of axially loaded as-built (control) RC column model. The plateau in the second portion of the curve is an indication of yielding of steel bars. The peak axial load and deformation were 740 kN and 10.08 mm, respectively. The deformation profiles of the control column are illustrated in Figs 5 and 6. Buckling of reinforcement bars was noticeable at the vicinity of the loading plate (Fig. 6).

Next, the as-built column is wrapped with two layers of CFRP sheets with 0° and 90° fiber orientations with respect to the hoop direction, to examine the effect of this strengthening technique on the column load and deformation capacities. The force versus displacement plot of the retrofitted column is presented in Fig. 7. The second portion of this bilinear plot demonstrates when the CFRP sheets become active in confining the concrete column. The maximum load and deformation were 1,880 kN and 11.82 mm, respectively. The column axial load capacity had increased 154% as compared to the control counterpart column due to the additional confinement provided by the CFRP sheets. The axial displacement capacity was also increased by 17% (Fig. 8). X-Z and Y-Z deformation views of FEA model of CFRP-strengthened RC column are shown in Figs. 9 and 10. No buckling was observed in the retrofitted column.

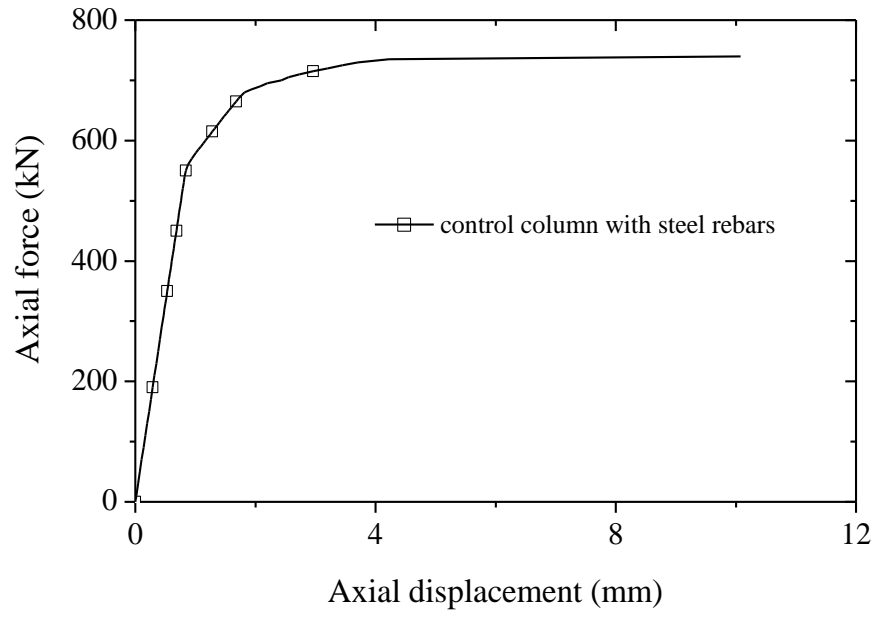


Fig. 4. Axial force-displacement behavior of FEA model of control RC column

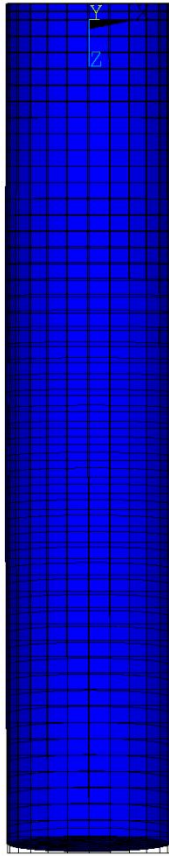


Fig. 5. X-Z deformation view of FEA model of control RC column

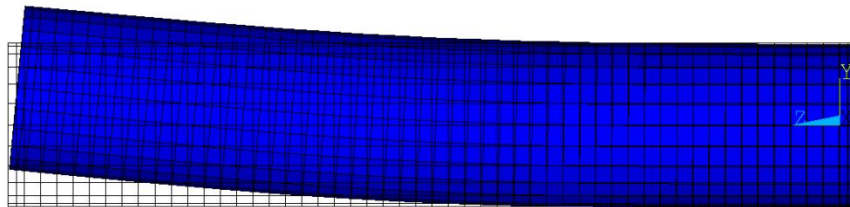


Fig. 6. Y-Z deformation view of FEA model of control RC column

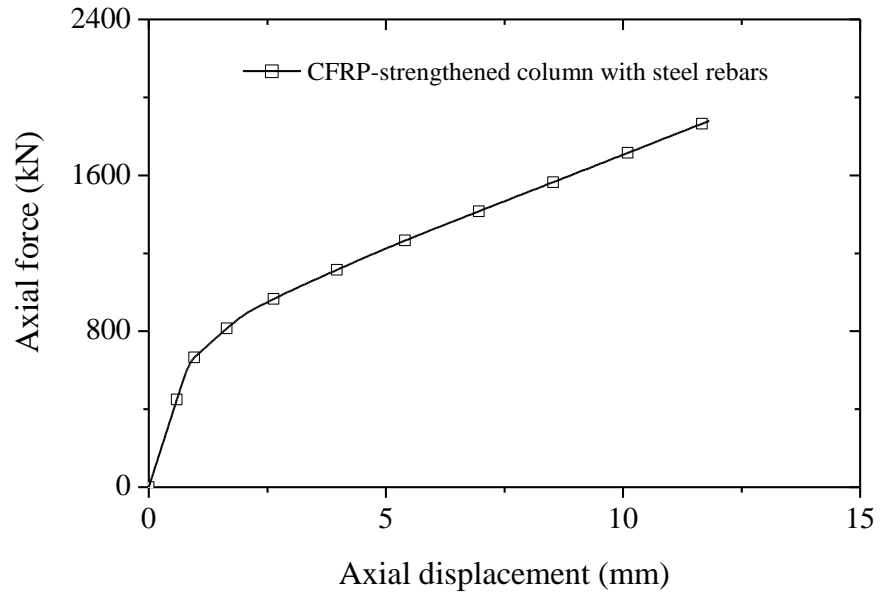


Fig. 7. Axial force-displacement behavior of FEA model of CFRP-strengthened RC column

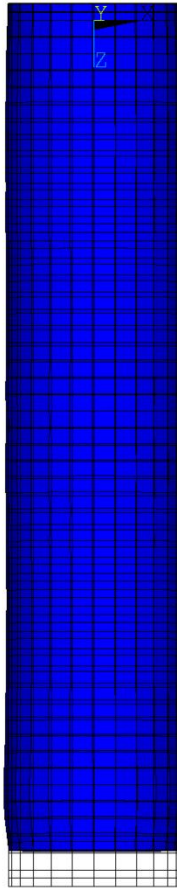


Fig. 8. X-Z deformation view of FEA model of CFRP-strengthened RC column

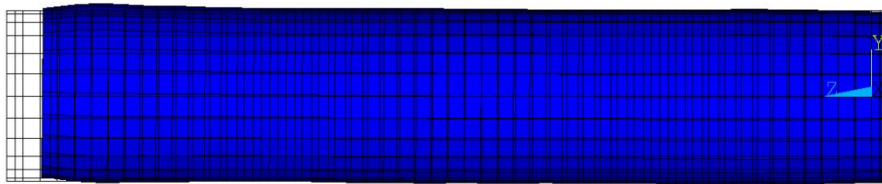


Fig. 9. Y-Z deformation view of FEA model of CFRP-strengthened RC column

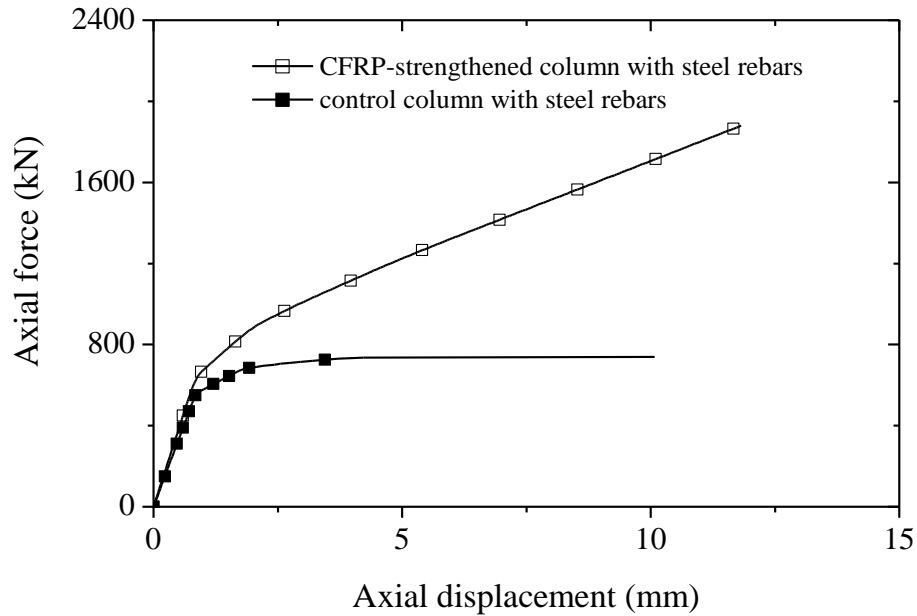


Fig. 10. Comparison of axial force-displacement behavior of FEA models of control and CFRP-strengthened RC columns

CONCLUSIONS

An innovative, reliable, fast, durable, and cost efficient FRP retrofit technique was proposed to enhance the capacity of RC columns that are in serious need of strengthening due to deterioration, accidental damage, or an increase in axial load demand. Nonlinear finite element analysis provided a great tool to investigate the behavior RC column models before and after retrofit through simulation. The external upgrade scheme using high strength, light weight, noncorrosive, durable, and sustainable composite material was able to enhance the capacity of the RC column. The axial load capacity of the CFRP-strengthened RC column was increased by more than 1.5 times when two layers of CFRP sheet were wrapped around the RC column. The CFRP external strengthening also controlled the buckling of the axially loaded RC column. The finite element analysis findings showed a great promise for the wide use of FRP retrofit including lateral confinement of the bridge piers to be able to withstand additional axial (gravity) load generated due to increased load requirements or excessive traffic loads. This retrofit

technique is also an excellent venue to repair the older bridge piers that have lost their cover overtime.

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