Title: *Use of Nano-Particle Enhanced Composites to Reduce Blast Vulnerability of Low Rise RC Frame Buildings*

Authors: Charlie Burchfield Graduate Research Assistant
Nitin Pangave Graduate Research Assistant
Mark Russell Undergraduate Research Assistant
Chris Mullen* Associate Professor

Department of Civil Engineering, 203 Carrier Hall
The University of Mississippi, University, MS 38677

Tezeswi Tadepalli Doctoral Candidate and Senior Engineer

Hinman Consulting Engineers, One Bush Street, Suite 510,
San Francisco, California 94104

*Presenter and corresponding author:
Tel: (662) 915-5370
Fax: (662) 915-5523
E-mail: cvchris@olemiss.edu

ABSTRACT

Ground floor columns in reinforced concrete moment frame buildings are vulnerable to severe damage due to external air blast loading. The loss of ground floor columns and weakening of adjacent ones can destabilize the structure and potentially trigger partial, progressive, or complete collapse of the building. A column damage evaluation procedure has been established based on nonlinear static analysis of a finite element representation of a typical column incorporating composite action of steel and concrete at the cross-section level. The procedure has been applied to evaluate blast vulnerability of a characteristic column in a typical low rise RC frame designed to meet 2006 International Building Code provisions for wind and seismic loading. The present work implements the procedure to generate an expanded database of column performance for a range of design cases. The database includes progressively larger cross-sections and steel ratios as might be required for taller buildings or more severe loading environments. The results indicate that the benefits of increasing gross concrete section size and steel ratio are not uniform. Fiber reinforced polymers and nano particle reinforcement show promise for increasing both strength and ductility depending on the material design selection and method of application. The database results provide a basis for effective selection of polymer based composites considering multi-hazard design objectives and loading regime or threat level in the case of blast.

INTRODUCTION

Recent natural and man-made disasters have highlighted the vulnerability of building construction to loss of column strength under severe loading. Building codes have for many years provided detailed design and detailing provisions enabling structural engineers to design frame structures to withstand severe lateral

---

C. Burchfield, N. Pangave, M. Russell, C. Mullen, University of Mississippi, 203 Carrier Hall, University, MS 38677, U.S.A.
T. Tadepalli, Hinman Consulting Engineers, One Bush Street, Suite 510,
San Francisco, California 94104

loads caused by high winds (e.g. Category 3-5 hurricanes) and moderate to severe earthquakes (e.g. M6-M8). Design for blast loading, however, has only recently been brought out of the military circles into the public domain primarily through guidelines developed for federally owned buildings [1].

An ongoing study at the University of Mississippi is investigating the benefits of using nano particle reinforcement to improve the blast performance of conventional building construction including concrete masonry unit (CMU) wall panels and reinforced concrete (RC) low-rise building frames prevalent in many of the communities throughout the United States but especially in less densely populated states like Mississippi.

The work discussed here represents a portion of the broader study that focuses on structural components and subsystems. A database of blast resistance of RC concrete columns designed to satisfy current building code provisions is being developed through computational simulations to guide building designers concerned about accidental or man-made external explosions. Results of component simulations [2] are being compared to high-fidelity simulations [3] to establish validity of the evaluation procedure. Preliminary indications show qualitative agreement and justification for assumptions made in the analysis described below.

COLUMN RESISTANCE CURVES

A nonlinear static finite element analysis procedure [2] has been implemented here for computing the lateral force and deformation resistance capacity of reinforced concrete columns of varying section dimensions and reinforcement sizes. Fixed ends are assumed to represent an upper bound on the restraint provided by frame action in a larger system. Monotonically increasing uniform lateral pressure is assumed to approximate the localized effect of a scenario blast event of given charge weight and offset distance from the exposed building face.

Figure 1 shows the basic column configuration and identifies design parameters for a square cross-section with steel longitudinal bars for bending resistance and transverse reinforcement for core concrete confinement and shear resistance. Also shown are the idealized blast loading and response conditions.

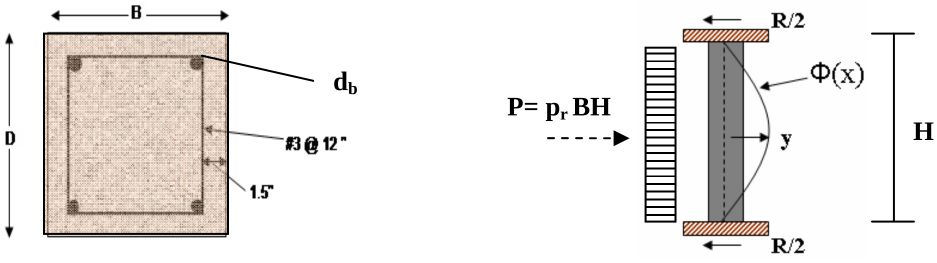

Figure 1. Column section design and loading parameters considered in the analysis.

A fiber section hinge model available in the commercial structural software SAP2000 [4] has been used to permit the nonlinear stress-strain response of concrete and steel to be captured in the cross-sections that undergo nonlinear bending. The hinge model allows for the composite action of steel and concrete during flexural rotation of the section. Independent verification of the hinge model has been achieved through a Matlab routine developed by two of the authors [5].

The design parameters of the section have been varied to show the effect of increasing gross section area and longitudinal steel ratio on the resistance, *R*, and mid-height displacement, *y*. Resistance curves computed for four section areas and three steel ratios are plotted in Figures 2 and 3.

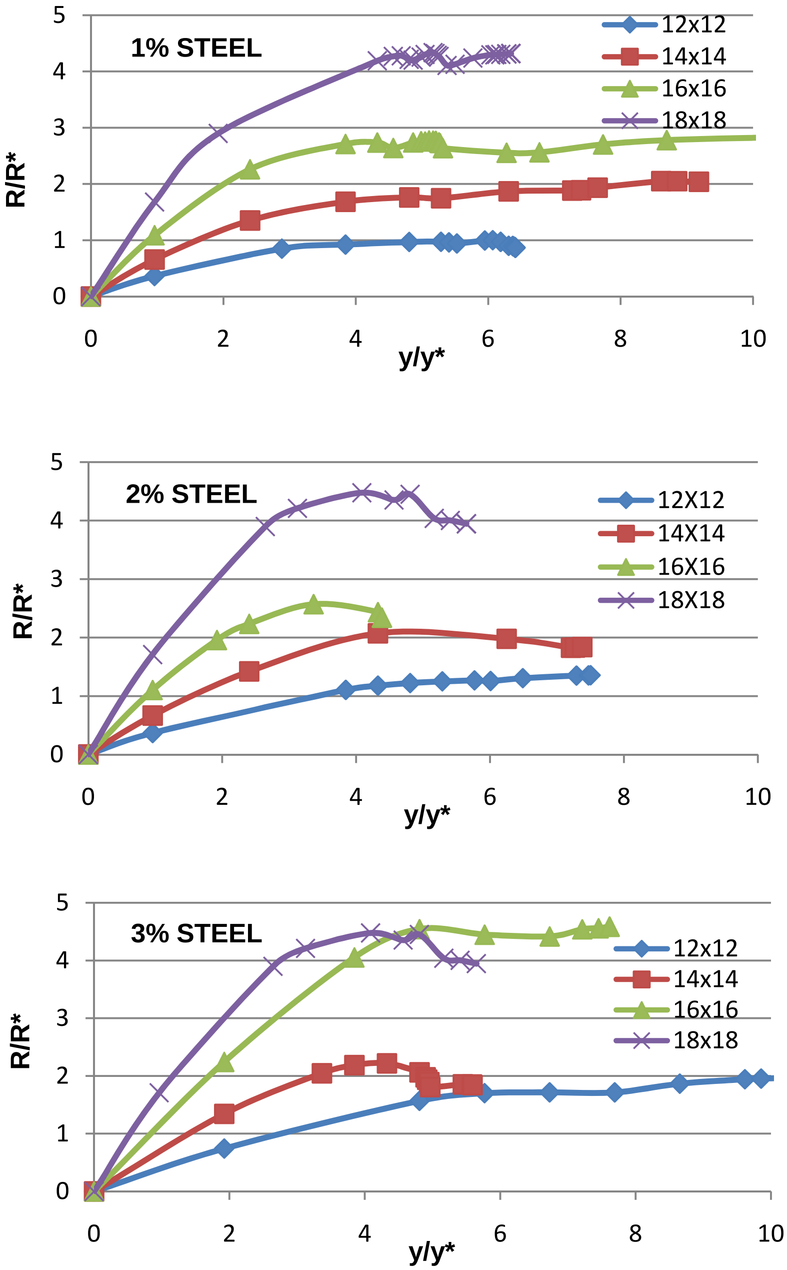

Figure 2. Column resistance curves showing effect of section size

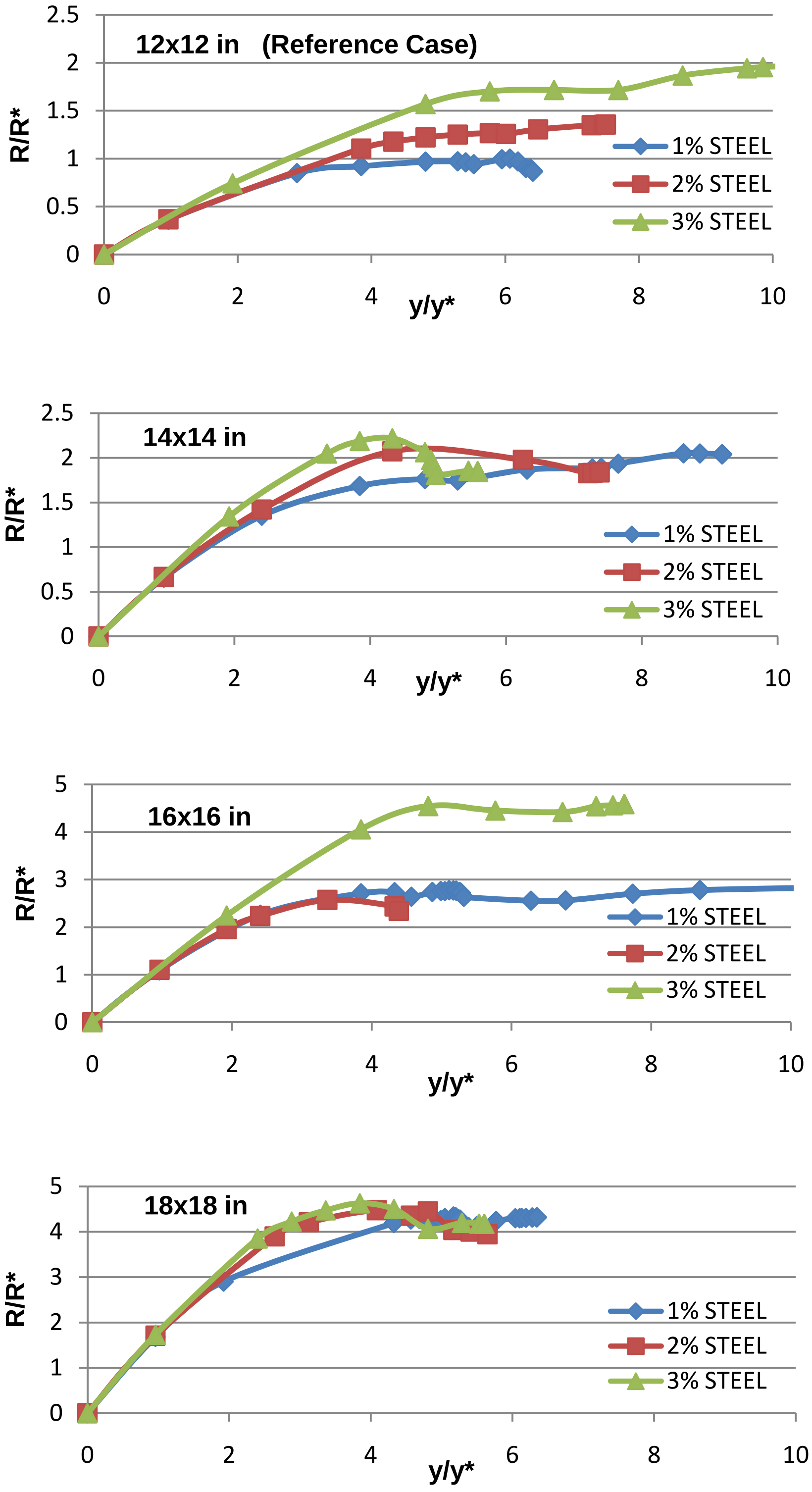

Figure 3. Column resistance curves showing effect of steel ratio

Figure 2 shows the effect of varying the section size for a select steel ratio, and Figure 3 shows the effect of varying the steel ratio for a select section size. The resistance values have been normalized with respect to the peak resistance, R^*, of the smallest section area and steel ratio (reference case) to show the benefits in terms of strength and deformation capacity. The displacement values have been normalized with respect to the displacement at which longitudinal steel first yields, y^*, for the reference case. This normalized displacement or ductility ratio is considered here in the range of 1 to 10. Numerical convergence issues preclude reliable resolution of the response beyond this range in most cases.

The simulation results plotted in Figure 2 indicate that, whereas for the reference case (lowest section size and steel ratio) increasing section size uniformly increases strength, the influence of section size on strength for the higher steel ratios is non-uniform and often negligible. This is not the case for stiffness which increases uniformly with section size for all steel ratios.

The same results recast in Figure 3 indicate that the load ratio can be doubled by increasing the section area by roughly a third. For the highest section size considered (slightly more than double the reference case), strength increases were nearly a factor of five. The strength increase comes at an increase in stiffness which may prove hazardous to the column by attracting more load as well as to the frame by altering its ability to distribute load and absorb energy. It is also observed in Figure 3 that, for all of the section sizes larger than the reference case, increasing steel ratio has no appreciable influence on strength (with one exception).

As mentioned above, the study is ongoing and careful examination of the fiber material stress and strain states in critical hinge sections for these cases will be performed to obtain further insight into the physical basis for these observed trends.

COLUMN PRESSURE-IMPULSE CURVES

The resistance curves provide the basis for identifying parameters of a bilinear SDOF oscillator approximation to the column response. The simpler model enables dynamic response under impulsive loading to be computed more easily. The assumption is that the column responds dynamically essentially independent of the frame because of the much higher natural frequency of the element relative to the system.

One of the authors has written a Matlab routine [2] to perform simulations of peak response under a wide range of pressure and impulse (or charge weight and off-set distance) characteristic of external blast loadings. For each pressure-impulse pair, the peak computed dynamic response of the oscillator is captured and used to represent the maximum displacement, y_{max}, at the column mid-height or, when normalized by the reference displacement, the maximum ductility ratio, y_{max}/y^*.

Figure 4 plots a family of curves representing pressure-impulse combinations that produce the same maximum ductility ratio. By correlating ductility demand and expected damage level, the curves can be used to assess performance or vulnerability from blast events of given intensity and to map damage for a given frame system [2].

The curves relate normalized pressure in terms of load (force) quantities to normalized impulse (force x time). Normalized pressure load, P/R^*, is defined here as the peak reflected pressure, p_r, from the blast at the position of the column multiplied by the exposed area, $A=BH$, of the column divided by the peak resistance, R^*. The normalized impulse is defined for computation purposes as the area under an idealized triangular shape pulse of given intensity, p_0, and duration, t_d, divided by a reference impulse, I^*. A reference impulse for a known blast event might be a useful choice, but in the absence of a conventional choice, we have chosen one reflective of the system properties. Here I^* is defined as the product of R^* and the oscillator natural period, $T_0 = \sqrt{K/M}$. Both R^* and K are obtained from the resistance curves. M is obtained as the fraction of the total column mass, $M_0 = BDH$, participating in the dynamic response. Here we use $M=0.72\, M_0$ based on energy considerations [6].

The results in Figure 4 show the trend of increasing ductility demand with increasing pressure and impulse. Further interpretation requires knowledge of the blast event parameters and the correlation between ductility demand and damage level.

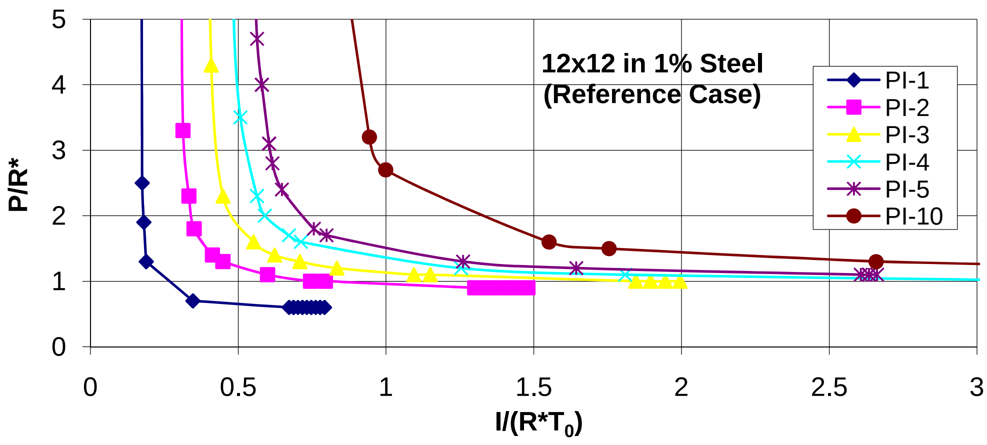

Figure 4. Pressure-impulse curves for reference case

OBSERVATIONS

In the context of a design or retrofit evaluation, target ductility demands may be used to determine the need for reinforcement. The choice of reinforcement depends on whether the need is increased strength, stiffness, or ductility. The resistance and pressure-impulse curves provide one possible basis for making such evaluations.

In a separate phase of the overall study, polymers reinforced with nano-size particles [7] have been shown to exhibit potential for providing both high strength and ductility in the application to CMU walls. Shock tube testing is planned as part of the overall study to validate these claims which to date are largely premised on computational simulation.

It is anticipated that these nano reinforced materials can offer a relatively low cost design or retrofit solution for both walls and columns found vulnerable to blast loading. Simulations such as those presented here offer a reasonable means of evaluating the performance and reinforcement needs as well as a rational basis for estimating the required quantities.

ACKNOWLEDGEMENTS

The authors wish to acknowledge financial support for this work provided through a subcontract to the Department of Civil Engineering at the University of Mississippi from the Department of Homeland Security-sponsored Southeast Region Research Initiative (SERRI) at Department of Energy's Oak Ridge National Laboratory.

REFERENCES

1. Tadepalli, T., and C. Mullen, May 2007. “Performance assessment of blast resistance for multi-hazard mitigation of RC frame structures in moderate seismic zones,” in *Structures Congress 2007*, Vancouver, Structural Engineering Institute, ASCE.
2. Tadepalli, T., and C. Mullen, May 2008. “Vulnerability of low rise buildings due to external blast events: Part 1 (damage mapping),” in *EM08*, Minneapolis, Engineering Mechanics Institute, ASCE.
3. O’Daniel, J., C. Mullen, and T. Tadepalli, “Blast effects on three-story frame building,” in *EM08,* Minneapolis, Engineering Mechanics Institute, ASCE.
4. Computers and Structures, Inc., 2006. “SAP2000 v11 User’s Manual,” Berkeley, CA.
5. Tadepalli, T., and C. Mullen, 2007. “Interactive computational tool for simulation of dynamic response and damage in composite structures,” *Composites Part B: Engineering,* (conditionally accepted).
6. Biggs, J., 1964. *Introduction to Structural Dynamics*, McGraw-Hill, Inc.
7. Irshidat, M., A. Alostaz, C. Mullen, A. Cheng, and R. Mantena, May 2008. “CMU infill wall blast simulation for optimizing performance of nano-particle enhancement of energy absorption and debris mitigation,” in *EM08*, Minneapolis, Engineering Mechanics Institute, ASCE.