

RETROFIT OF REINFORCED CONCRETE COLUMNS USING COMPOSITE WRAPS TO RESIST BLAST EFFECTS

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ABSTRACT

Analyses were conducted to demonstrate the effectiveness of composite wrapped columns for improving the survivability of existing reinforced concrete multistory buildings to attacks by explosives. Different standoff distances and charge sizes were considered. Two building designs were analyzed: one in which the building members were designed primarily for gravity loads (UBC seismic zone 1) and one in which the members were designed to resist seismic loads (UBC seismic zone 4). Structural response predictions were performed with the three-dimensional Lagrangian finite element code DYNA3D, using a concrete material model especially designed to predict nonlinear concrete responses to explosive loads. The results indicate that under some circumstances composite wrap can be an effective means to retrofit an existing facility to lessen its vulnerability to blast loads.

Keywords: blast effects, reinforced concrete, composites, FRP.

INTRODUCTION

A study [Ref. 1], based on numerical analyses performed by DYNA3D, confirmed the vulnerability of conventional reinforced concrete multistory buildings to attacks by explosives. The focus of these analyses was on the prediction of the survivability of the perimeter columns of a typical multistory building when subjected to blast loads from a possible terrorist explosive device. Two building designs were analyzed: one in which the building members were designed

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mainly for gravity loads (UBC seismic zone 1) and one in which the members were designed to resist seismic loads (UBC seismic zone 4). Both cases were considered since the zone 4 design includes significantly higher lateral reinforcement (for confinement purposes) which enhances the resistance to shear.

Numerical analyses have demonstrated [Ref. 1] that structural collapse of a multistory building as a whole may start by the failure of perimeter columns on the first floor. Retrofit techniques consisting of strengthening the columns with round steel jackets were assessed and found to markedly increase the survivability of the columns [Ref. 1].

In this paper the effect on the survivability of columns wrapped with composites will be examined using the same numerical analyses methods previously used for the steel jackets. Structural response predictions are computed with the three-dimensional Lagrangian finite element code DYNA3D [Ref. 2], using a concrete material model especially designed to predict nonlinear concrete responses to explosive loads. This study also includes the use of different charge sizes and standoffs so that architectural considerations that limit the threat (*e.g.*, increasing standoff) can be evaluated.

MODELING OF COLUMNS FOR BLAST ANALYSIS

To simplify the problem of computing the response of the columns only a portion of the multistory building is modeled, as indicated in Figure 1 and shown in Figure 2. The focus of the analysis is the response of the first floor column. The other portions of the structure shown in Figure 2 are included to provide the correct boundary condition for the first floor column. To further simplify the problem, the loading applied consists of only airblast (*i.e.*, fragment and debris effects are ignored) and is applied only to the columns; engulfment is ignored. The airblast was generated separately using closed form expressions derived from data (*e.g.*, as described in Ref. 3). The pressures reflected off the exterior surfaces are predicted with relatively high fidelity (in contrast with the pressure field inside the building, which is complex and difficult to predict).

Some of the significant features of first principle calculations presented in this paper are the inclusion of the effect of confinement on the concrete strength and ductility, the effect of strain rate (*i.e.*, apparent material strengthening due to rapid loading), and the capability to model the direct shear responses (*i.e.*, dynamic shear failure [Ref. 4, 5]). A major issue in computing the column response is related to having sufficient fidelity in the modeling to capture both localized shear and bending failure mechanisms. The localized shear response, which occurs in the first few milliseconds of the column's overall response, is especially important to predicting the survivability of reinforced concrete columns. Gravity effects are also included through the application of the load at the top of the column as shown in Figure 2.

ANALYTICAL PROCEDURE USED TO EVALUATE THE RETROFITS

Conventional Multistory Design. To measure the effectiveness of the various retrofit designs, a baseline design for a multistory building (Figure 1) was generated, as shown in Figures 3 and 4. Two designs were developed: one in which the columns and beams were

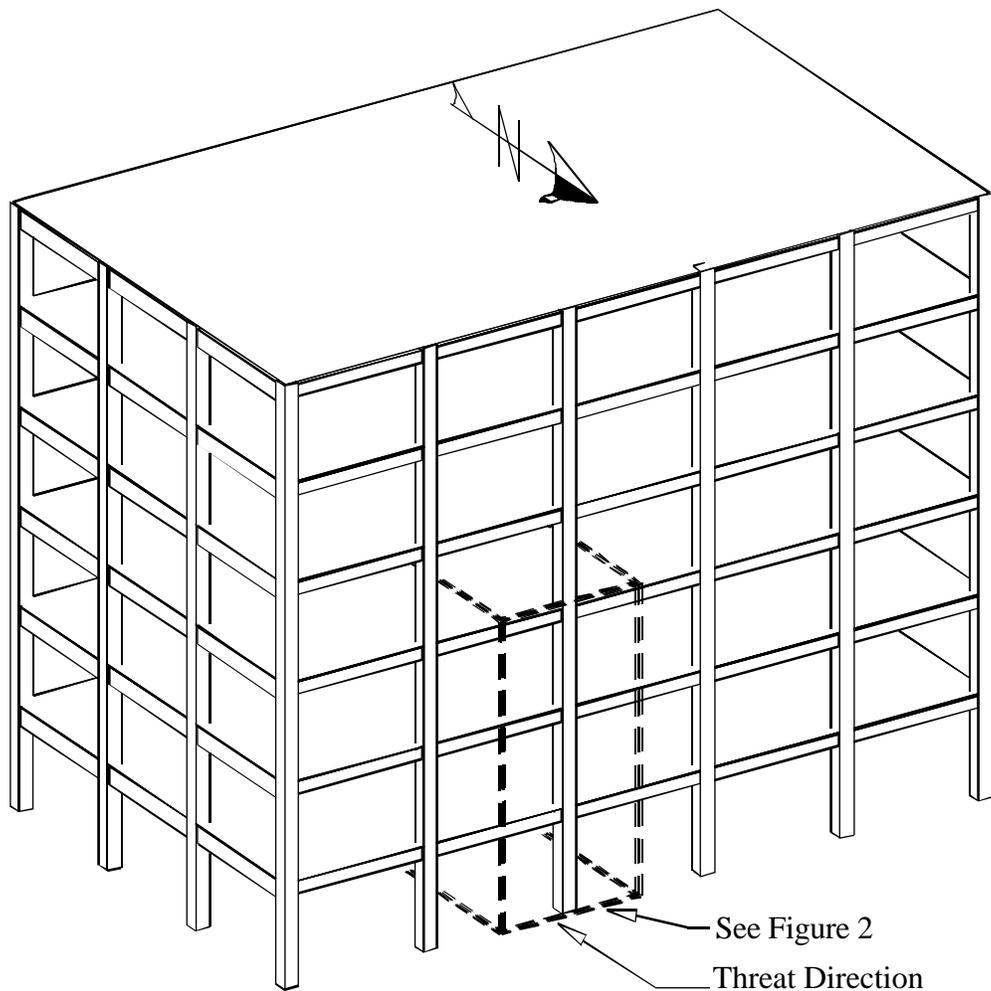


Figure 1. Overview of multistory building used in evaluation.

designed mainly for gravity loads (*i.e.*, consistent with UBC seismic zone 1) and one in which the columns and beams were designed to resist seismic loads (*i.e.*, consistent with UBC seismic zone 4). This allows the evaluation to include the effects of the increased ductility and ultimate strengths associated with a building designed for a highly active seismic zone.

Portion of Building Used for Analysis. To reduce computational demands, only a single bay from the bottom three stories of the building is used for the response predictions (Figure 2). Symmetry is assumed along the east-west edges of this section. While this is an approximation, it does produce a model of reasonable accuracy and size for evaluating the effects of composite wrap. To keep the model simple with little compromise to the column response, the south edge of the bay floor and girders are fixed at the location of the first interior column.

Loading. Airblasts at three different ranges (*i.e.*, 10, 20, 40 feet) were calculated for two different ANFO charge sizes (*i.e.*, 1,500 and 3,000 lb). The peak reflected pressure and impulse at the mid-height of the first floor column are given in Table 1. The gravity load is applied to

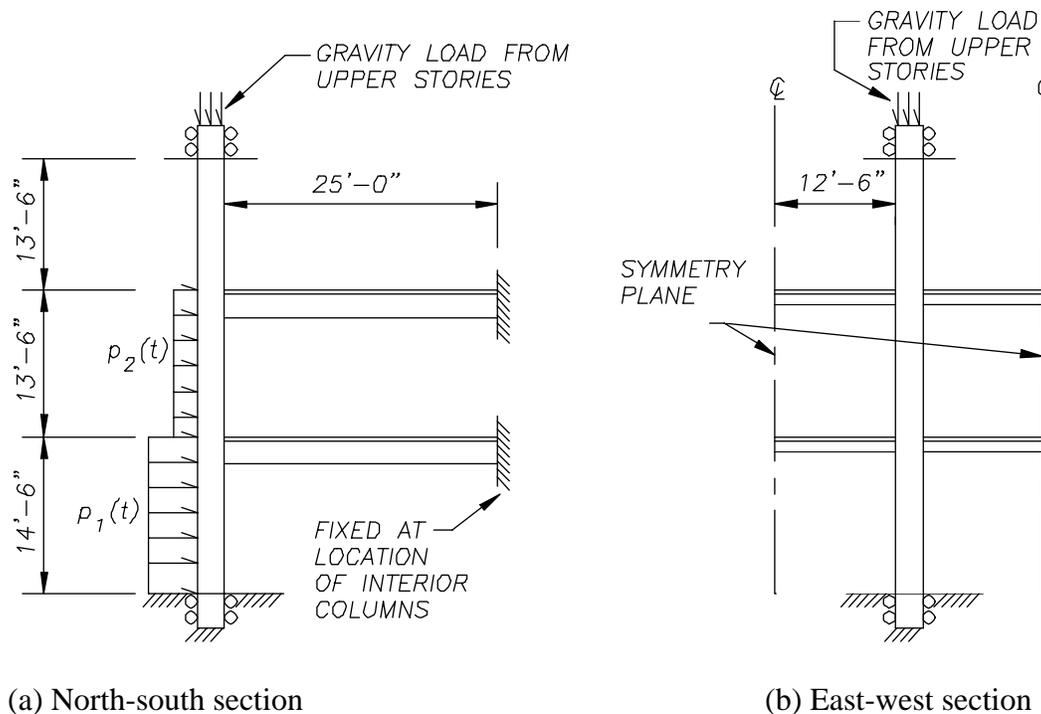


Figure 2. Sections modeled in the analyses.

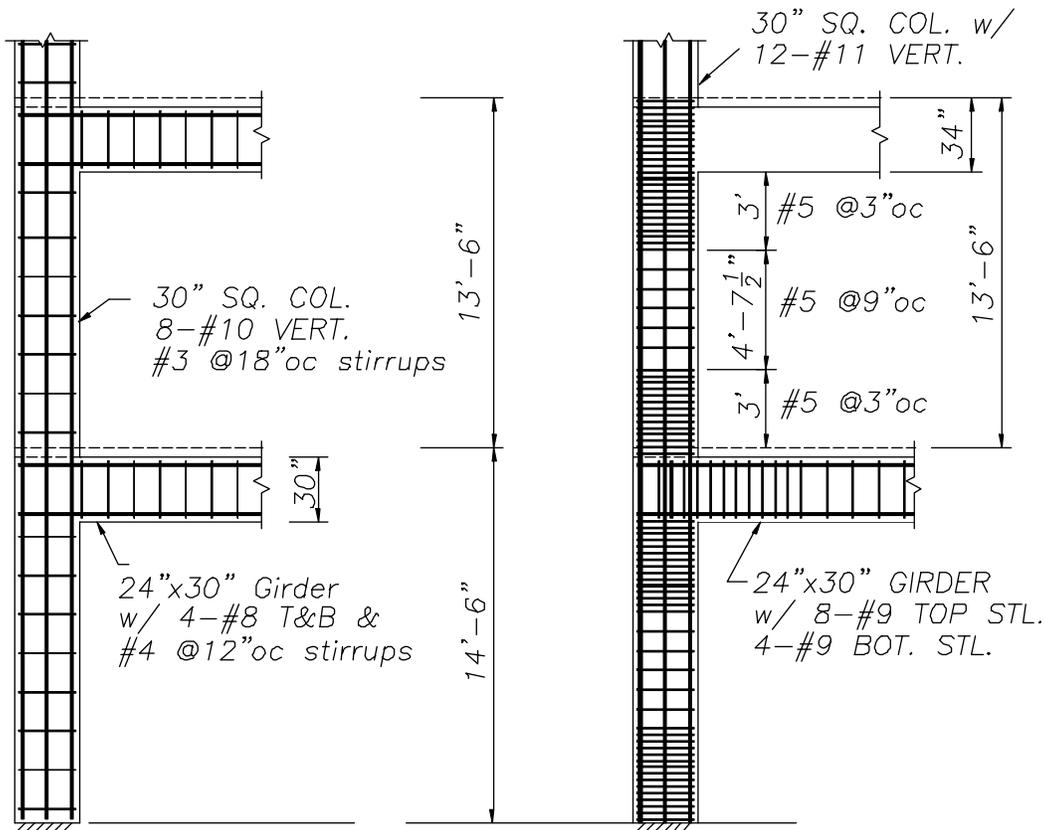
each element in the mesh; the gravity load from the upper stories is applied as a pressure load over the top of the column, as shown in Figure 2. Different pressure histories are applied to the exterior faces of the first and second story columns.

Material models. The material models for the concrete and steel reinforcement include elastic-plastic behavior, rate effects, and fracture. The new concrete material model implemented in DYNA3D [Ref. 7] includes softening together with a fracture-energy based localization limiter to prevent any spurious mesh sensitivity. For the analyses, an ASTM A 615 Grade 60 steel was used for reinforcement, with a rupture strain of 13%. The concrete had a

Table 1 - Characteristics of airblast loads applied to the first story

Load Case Number	Charge Size lb (Kg)	Standoff ft (m)	Peak Reflected Pressure psi (MPa)	Peak Reflected Impulse psi-s (KPa-s)
1	1500 (682)	10 (3.05)	8100 (55.9)	3.7 (25.5)
2		20 (6.10)	2500 (17.2)	1.7 (11.7)
3		40 (12.2)	420 (2.9)	0.9 (6.2)
4	3000 (1364)	10 (3.05)	12000 (82.7)	6.9 (47.6)
5		20 (6.10)	4400 (30.3)	3.2 (22.1)
6		40 (12.2)	840 (5.8)	1.6 (11.0)

Note: height of burst was 6 feet (1.83 m)



(a) Section for UBC zone 1 building

(b) Section for UBC zone 4 building

Figure 3. Typical details associated with the building for a north-south section.

nominal strength of 5,000 psi (34.5 MPa). For this particular study a relatively weak carbon wrap was used with a thickness of 0.019 inch (0.5 mm) per layer, a strength of 54 Ksi (372 MPa) and a stiffness of 7600 ksi (52 GPa). Only six layers of the composite were applied (additional layers would further stiffen the column and reduce the deflections). Figure 5 depicts some of the behaviors modeled for the concrete. Material data and details for the material models are given in References 7 through 11.

Composite wrap concepts. The chief benefit of wrapping a reinforced concrete column with a composite is gained from the effect that increased confinement has on the strength and ductility of concrete, as shown in Figure 5. In this application the wrap will be most useful in mitigating direct shear failure [Ref. 12], but it can also provide increased axial and bending capacities [Ref. 13]. Composite or fiber reinforced plastic (FRP) wrap are most effective when circular, which requires a grout fill as depicted in Figure 6. Figure 6 depicts the wrap designs used in this study for the columns on the first and second floors of the building shown in Figure 3. This type of column wrap has been shown to significantly increase the column ductility, typically from a ductility of 1.5 to 10 [Ref. 12, 13]. As a consequence this type of column retrofit (using either steel or FRP jackets) has been extensively applied in California for highway bridge columns [Ref. 14].

The column wrap concept is primarily dependent on the lateral dilation of the concrete causing an increase in its confinement by forcing the wrap into circumferential tension. Concrete in uniaxial unconfined compression exhibits a constant Poisson ratio of about 0.2 until approximately 75% of the compressive strength, corresponding to a volumetric compression phase. At that point extensive internal cracking starts developing and the apparent Poisson ratio starts increasing to 0.5, where there is no further volume variation. For increasing compression the apparent Poisson ratio keeps increasing until the overall volumetric strain becomes zero, then becomes positive (net volume increase). This is shown in qualitatively in Figure 7 [Ref. 15]. The ability of the numerical material model to reproduce the volumetric expansion phase is the key to the proper representation of the confinement effect. Figure 8 shows the corresponding output from the new concrete material model for a single concrete element in uniaxial unconfined compression. As a secondary benefit (*i.e.*, to the increased confinement), the wrap provides additional shear reinforcement.

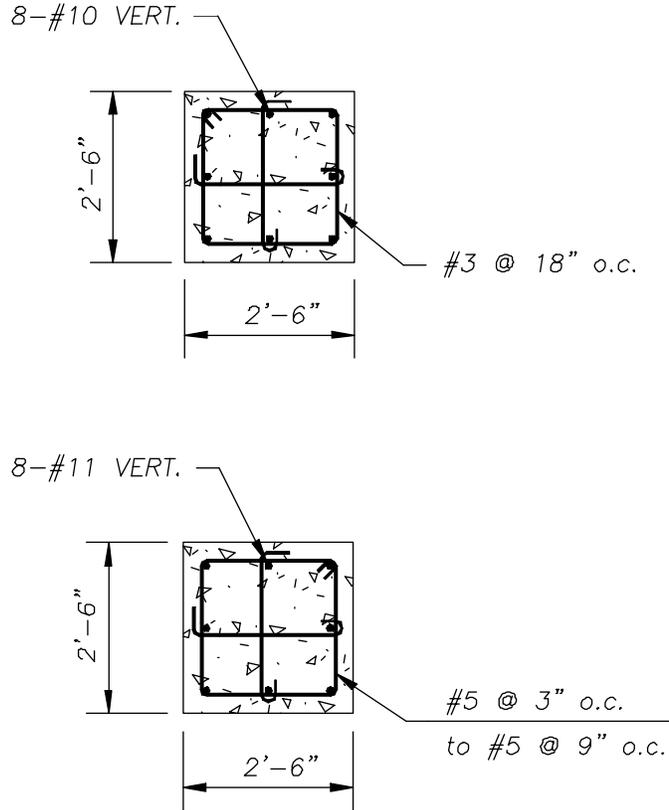


Figure 4. Column cross sections.

With respect to the composite material, although carbon (or graphite) and glass fibers have typically been used for column retrofits [Ref. 14], aramid fibers (*e.g.* Kevlar) may be more appropriate for blast loads, due to their impact resistance.

Mesh. The concrete portions of the columns and girders are modeled with three-dimensional eight-node brick elements; the reinforcement is explicitly modeled with truss elements. Shell elements, which replicate the nonlinear flexural behavior, are used to model the floors and floor joists. The mesh for the *as is* columns (*i.e.*, without composite wrap) is shown in Figure 9.

VALIDATION OF RESPONSE PREDICTIONS

There is not much experimental data in the open literature by which to evaluate the accuracy and applicability of the models used to predict the effects of blasts on structures. Most test data is either compromised because of its incompleteness (*e.g.*, lack of complete material characterization), fatally flawed (*e.g.*, ill-defined boundary conditions as often occurs in tests involving single structural members, such as slabs and beams), or is derived from weapons effects programs and is not widely disseminated. One validation study that is available for models

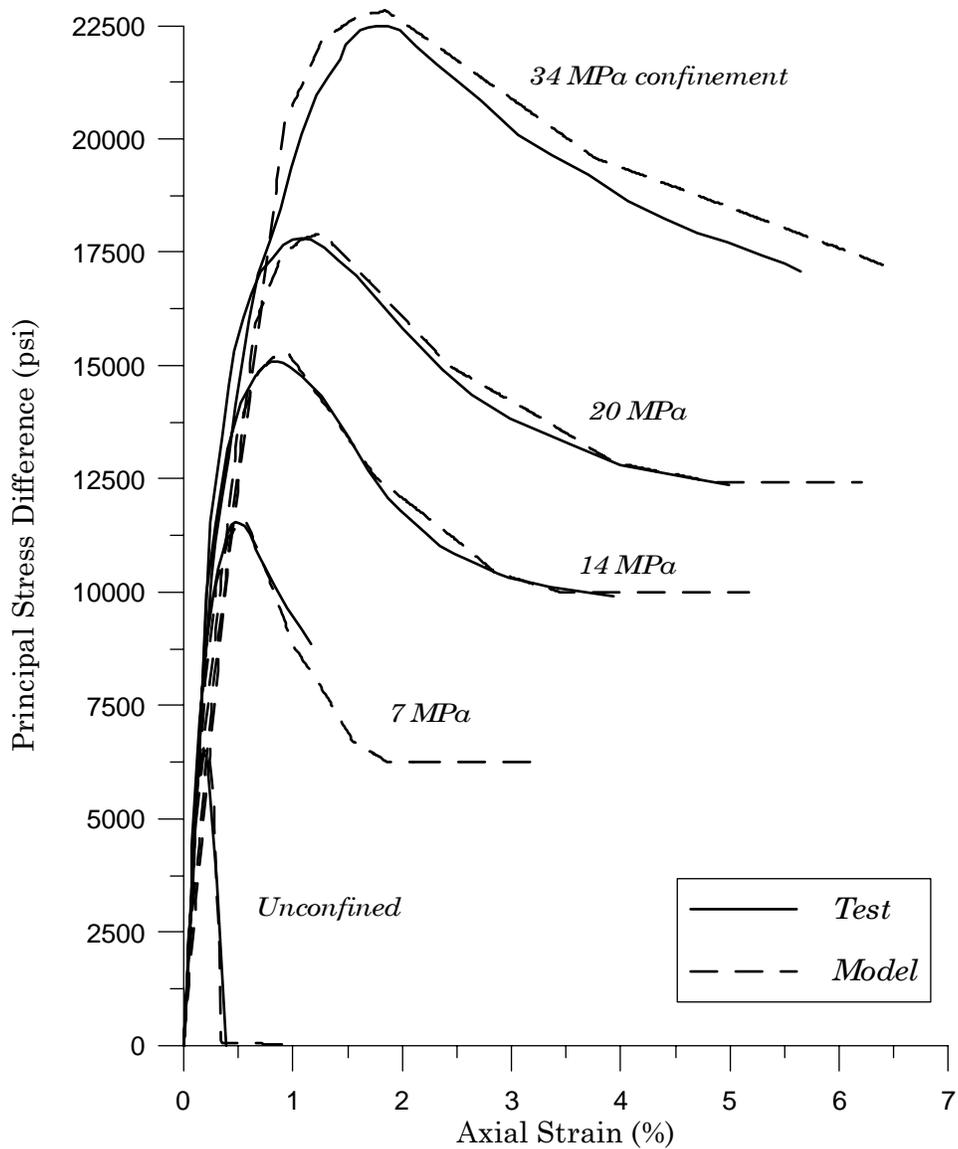


Figure 5. Fit of material model to experimental data for concrete.

similar to the ones shown in this paper is presented in [Ref. 6]. That paper studied the response of substantial dividing walls to close-in charges. The metric for validation was the velocity of the debris, which were predicted within 10% of the test data.

ASTM C39 compression tests carried out on 6-inch (15.2 cm) diameter concrete cylinders jacketed with two layers of a carbon composite resulted in a strength increase of 20% at a peak strain of about 0.005. Figure 10 shows the test results for plain and jacketed concrete cylinders. Figure 11 shows the DYNA3D predictions for both cases. It is apparent that the concrete material model is able to properly represent the jacketing effects.

EFFECT OF RETROFITS

The response of the *as is* column is illustrated by a plot of the deformed shape of the first floor perimeter column shown in Figure 12(a). The corresponding response for the circular composite wrapped column is shown in Figure 12(b) for comparison. As can be seen from the results, a circular composite wrap can have a substantial beneficial effect on the performance of the columns.

Table 2 provides a summary of the midspan deflection for the various column designs considered. For a small standoff of 10 feet (3.05 m), the unwrapped column fails for both charges, but a circular composite wrap can prevent the failure for the smaller charge. For a standoff of 40 feet (12.2 m), no failure is predicted. Zone 4 columns are somewhat more resistant to shearing. The thickness of the composite wrap can be increased to make it effective or a different (*i.e.*, stronger or stiffer) fiber might be used.

CONCLUSIONS

The effects of standoff and composite wrap on enhancing the blast resistance of conventional reinforced concrete columns were analyzed. It was shown that the direct shear failure of first floor perimeter columns is a potential major collapse mechanism for the building as a whole. Wrapping the columns with a circular composite wrap prevents collapse for most of the cases studied. Square composite wrap columns did not perform as well as the circular wrapped ones; for example, only a slight improvement from 1.9 inches to 1.6 inches (mid-height displacement) occurred for the 20-foot standoff 1,500 lb charge, see Figure 13. However, using a stiffer carbon fiber (*e.g.*, $E = 15 \text{ Msi}$) would reduce the mid-height displacement from 1.6 to 0.9 inches. This is consistent with static tests on square wrapped columns. Adding a slight curvature (*e.g.*, a 2-inch radius) to the corners of these 30-inch square

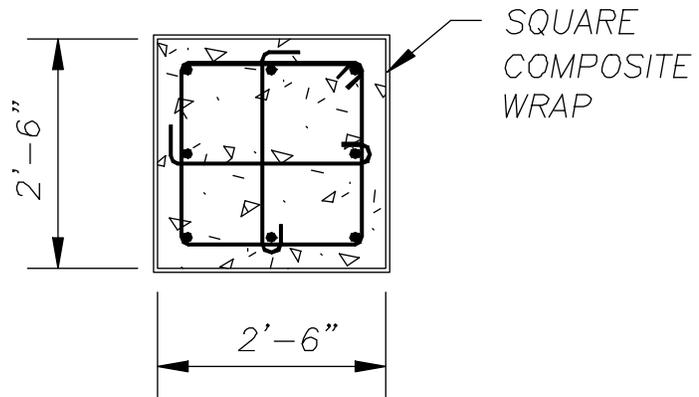
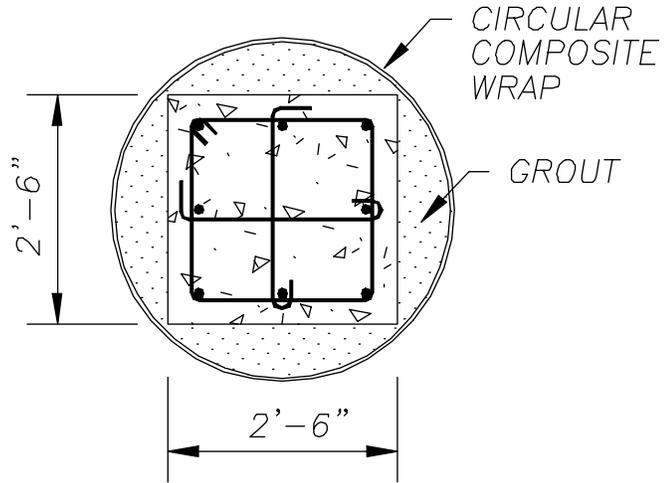


Figure 6. Wrap designs for zone 1 (zone 4 design is similar).

columns has been found in static tests to markedly improve the response of the columns. This design concept will be examined in a future paper.

Table 2 - Maximum displacements for first floor perimeter column.

Standoff ft (m)	TNT Yield lb (Kg)	Maximum Midspan Displacement, in (cm)				
		Zone 1			Zone 4	
		No Wrap	Circular Composite Wrap	Square Composite Wrap	No Wrap	Circular Composite Wrap
10 (3.05)	1500 (682)	failure	5.2 (13.2)	—	failure	4.3 (11.0)
	3000 (1364)	failure	failure	—	failure	14 (35.3)
20 (6.10)	1500 (682)	1.9 (4.8)	0.7 (1.8)	1.6 (4.1)	0.96 (2.4)	0.5 (1.3)
	3000 (1364)	failure	3.5 (8.8)	failure	failure	2.9 (7.4)
40 (12.2)	1500 (682)	0.17 (0.4)	safe	—	safe	safe
	3000 (1364)	0.79 (2.0)	safe	—	safe	safe

Notes: 1 ft = 0.3048 m, 1 in = 2.54 cm, 1 lb = 0.454 Kg

For the cases where similar calculations indicated that no failure would occur the column was deemed safe.

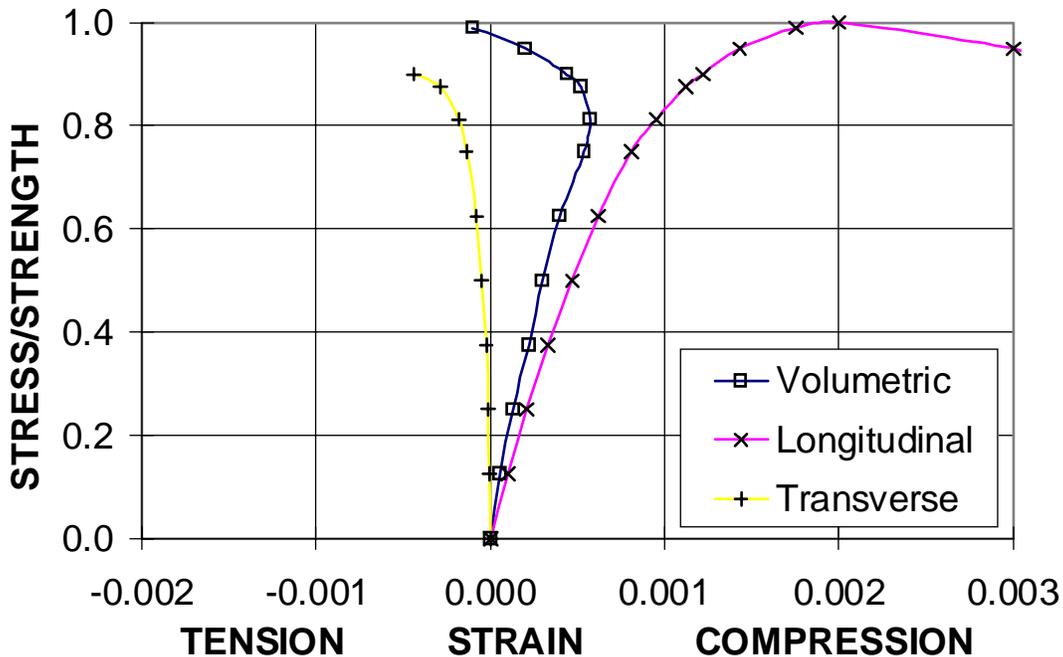


Figure 7. Typical strain histories in an uniaxial unconfined compression test.

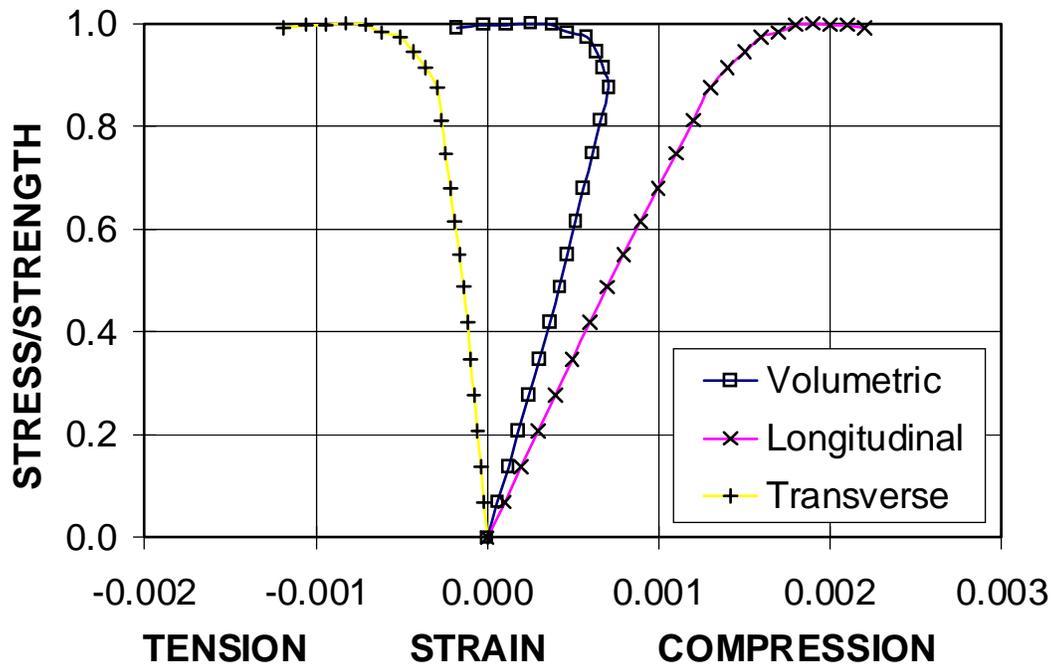


Figure 8. Numerical model strains for a uniaxial unconfined compression test.

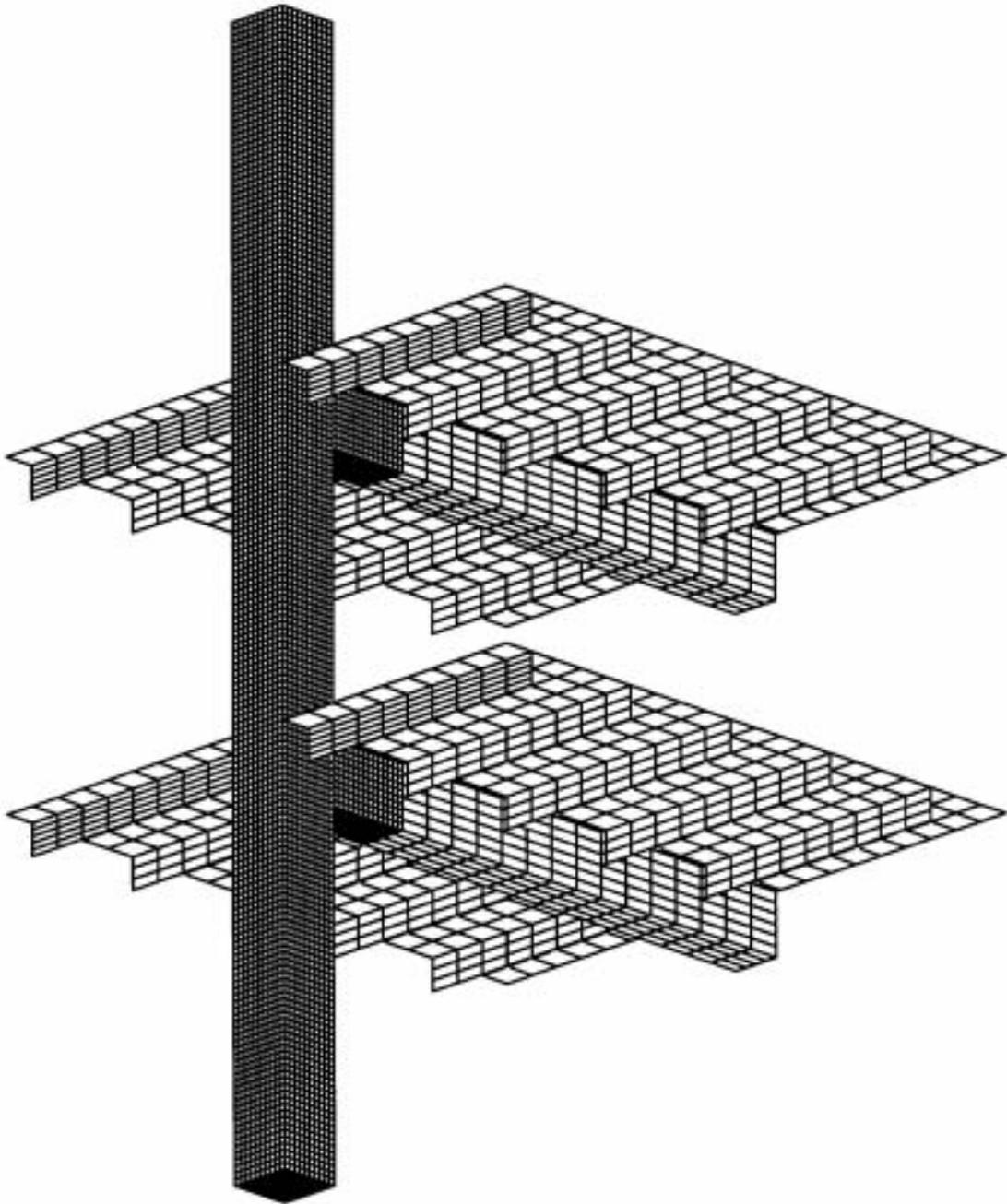


Figure 9. Mesh for the portion of the building studied

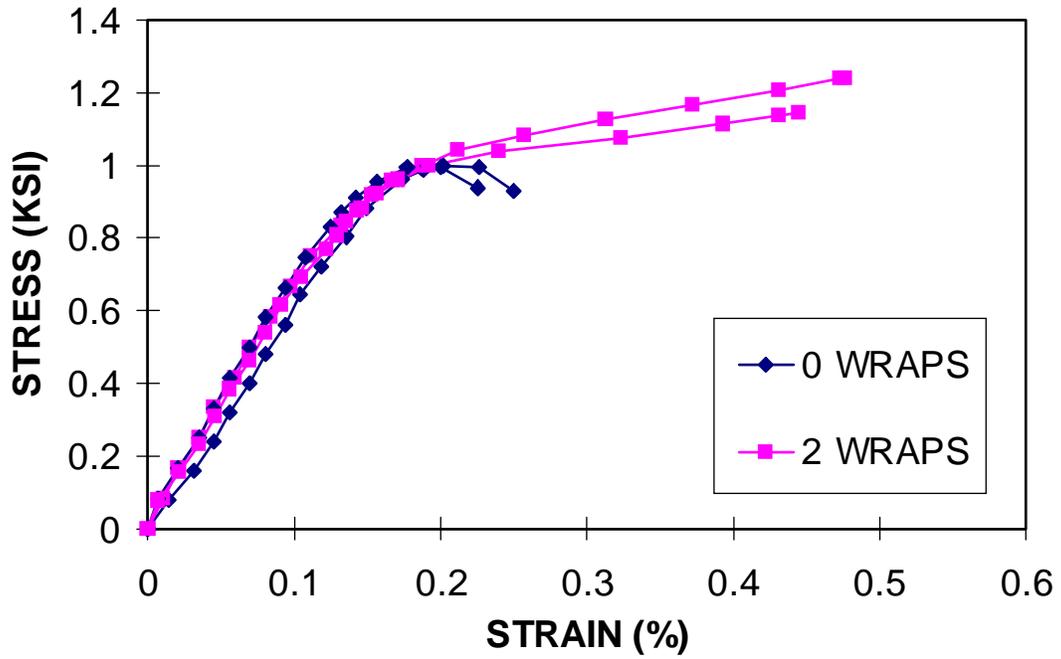


Figure 10. Compression test results on standard cylinders with and without wraps.

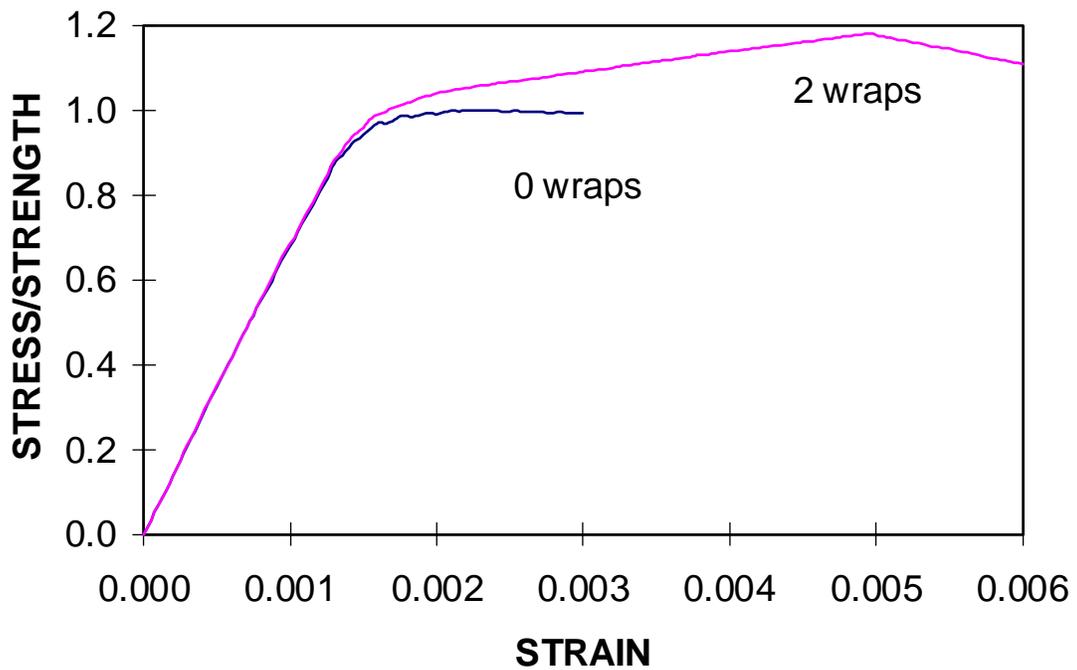
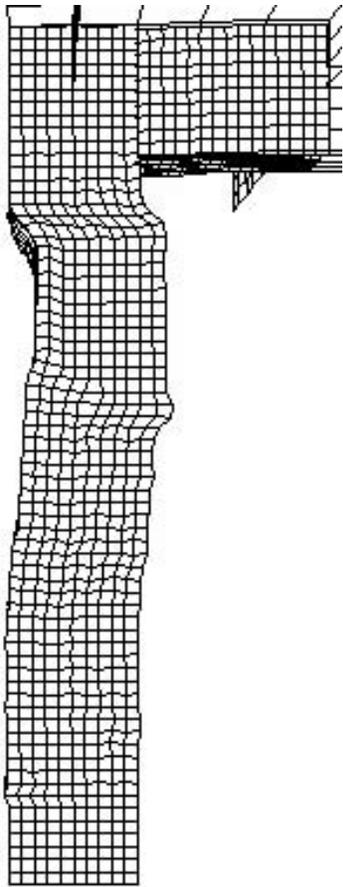
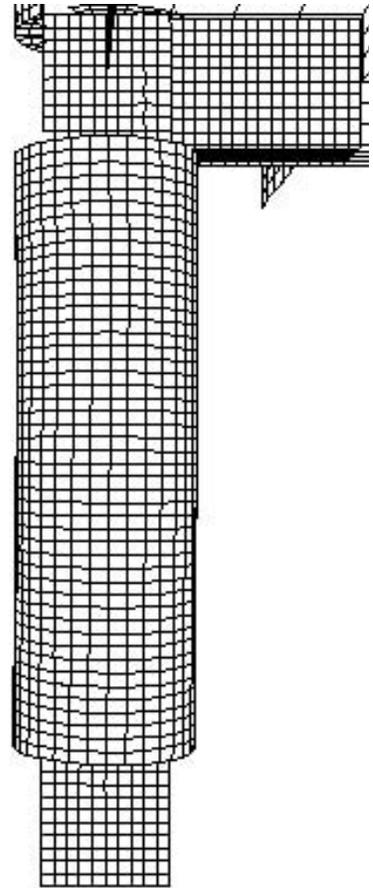


Figure 11. Numerical model of cylinder compression test.

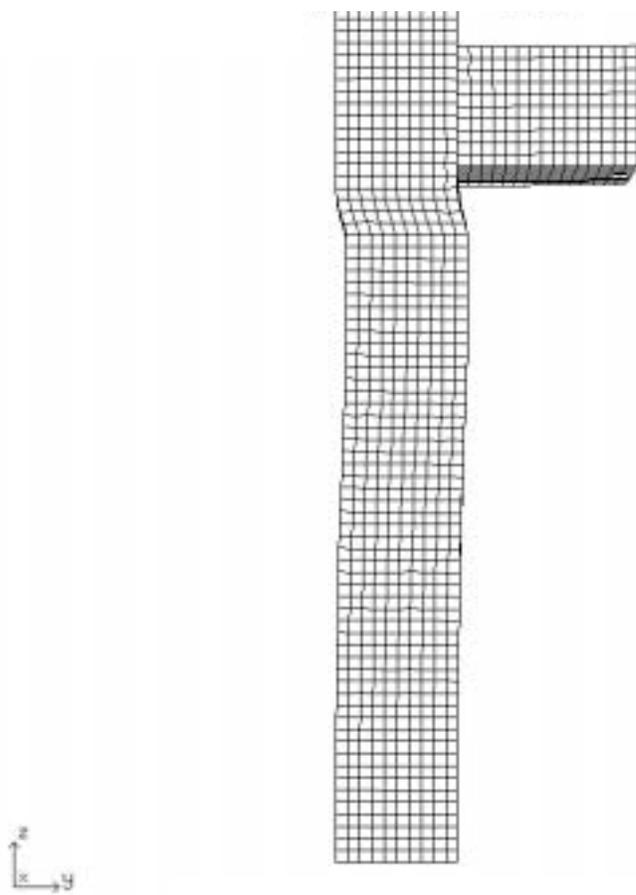


(a) Conventional.



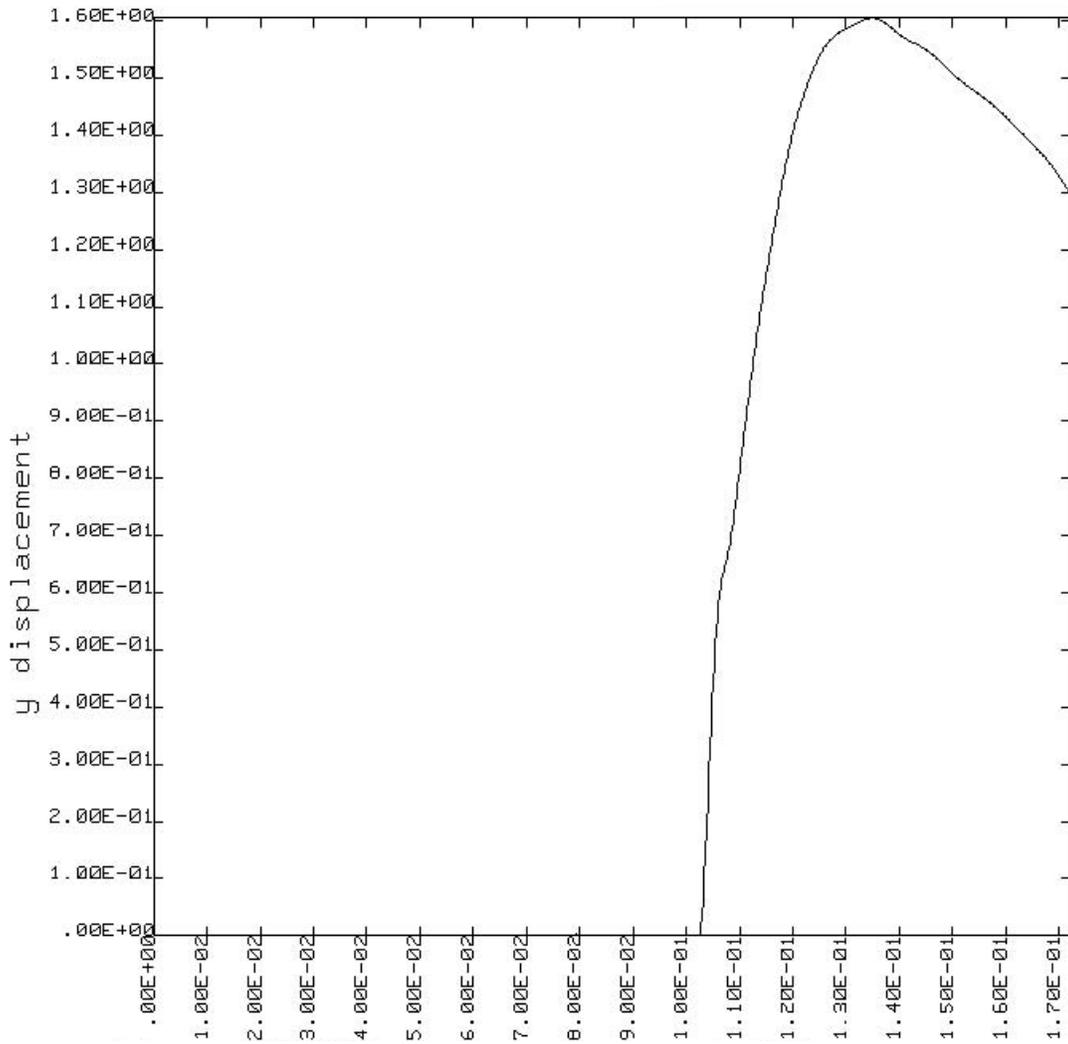
(b) Circular wrapped.

Figure 12. Response of zone 1 first floor column for a 20-foot standoff and 1,500 pound charge.



(a) Deformed shape.

Figure 13. Response of zone 1 first floor column for a 20-foot standoff 1,500 lb charge for square wrap.



(b) Time history of horizontal displacement at mid-height of first floor column.1

Figure 13. Response of zone 1 first floor column for a 20-foot standoff 1,500 lb charge for square wrap (continued).

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