# US Army Centrifuge: Progressive Collapse Testing of a 4-Story Reinforced Concrete Structure at 1/18-Scale

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**Abstract:** A 1/18-scale model of a 4-story reinforced concrete structure was tested at 18 g in the US Army Centrifuge to support the development of computational modeling of progressive collapse of multi-story buildings. The model structure was 4 bays long and 3 bays wide with column spacing about 33 cm in each directions and story height of 20.3 cm. Three columns around one corner at the 1st story were explosively removed while the model was spinning in the centrifuge at 18 g. The column removal resulted in complete collapse the bays above those columns but collapse did not progress to the rest of the structure.

### INTRODUCTION

obtained through a number of trade-off evaluations that balanced the objectives of the test program, the model dimensions as a function of scale, availability of threaded steel rods to simulate rebar, and the size of the centrifuge platform. The final design at reduced scale had to be consistent with design codes and within common practice for bar size selection, splices, hooks, concrete cover, etc. The result of the trade-off evaluations was to select a scale factor of 1/18.

### MATERIALS

The main steel reinforcing bars in the beams and columns were modeled with steel threaded rods. Previous investigations showed that the threads provide a reasonably good match to the bond between full-scale rebar and concrete [1, 4]. The nearest matches of standard thread sizes to the desired rod diameters are 1-64 threads for 1/18-scale #9 bars and 2-56 threads for 1/18-scale #11 bars. The pitch diameter of the 1-64 thread is about 1.5 mm and the pitch diameter of the 2-56 thread is about 1.7 mm. For comparison, 1/18-scale diameters of #9 and #11 bars are 1.6 mm and 1.9 mm, respectively.

A supply of rods of both sizes in 33 cm lengths was acquired by special order from Rolled Threads Unlimited, Waukesha, WI. Because the threading process induces strain hardening in the steel, the supplier adjusted the annealing schedule during the cold-drawing of the bare wire in order to approximately match the desired strength of the finished threaded rods. No heat-treatment of the rods was done after threading.



Figure 1. Beam-column rebar detail of the 1/18-scale model.

The main steel reinforcing bars in the floor slabs and the stirrups in the columns and beams were modeled with smooth steel wires because using threaded rods at the diameters required was considered impractical. The #5 and #4 rebar called for in the full-scale design were modeled with 0.89 mm diameter and 0.76 mm diameter wire, respectively.

Typical tension test results are plotted in Figure 2. In these plots, the measured force vs. strain was converted to effective stress vs. strain using areas computed by scaling #4, #5, #9 and #11 rebar by  $1/18^2$ . In the first portion of each curve, the strain was measured with a 2.54 cm extensometer attached to the rod. In the second portion, the strain was computed from the cross-head displacement and the 5.08 cm gauge length between the grips. Because the threaded rods exhibited essentially no hardening beyond about 2% strain, the ultimate strains are highly dependent on the gauge length. For all rod sizes, the strengths were very uniform but generally a little lower than desired to match Grade 60 properties.

The model concrete was a close approximation to the Fine Aggregate Cementitious Material (FACM) developed by the U. S. Army Corps of Engineers ERDC [8]. This material was selected because it has an aggregate size appropriate for the 1/18-scale structure and it has mechanical properties that are a good match to full-scale concrete. In addition, a significant amount of laboratory testing has been performed on FACM, facilitating the calibration of a constitutive model for computational predictions. FACM uses masonry sand. Figure 3(a) shows a comparison of the size distributions. In both distributions, the largest grain size is about 1.5 mm which is equivalent to about 2.54 cm at full scale.

The batch mix design for the model concrete is given in Figure 3(b). Mixing was done in a pan mixer in 23.15 kg batches. The proportions of the mix vary slightly from ERDC FACM because the fluidity had to be increased to place the SRI FACM in the column forms. In consultation with ERDC, trial batches were made at SRI with adjustments to increase the fluidity. The aggregate-to-cement ratio (A/C) was reduced slightly and the amount of fluidizing add mixture was

increased slightly but the water-to-cement ratio (W/C) was held constant so that the mechanical properties would be minimally affected.

Static compression tests on 7.62 cm diameter cylinders of SRI FACM at age 40 days were performed by Dynamic Consultants (DCI), Mountain View, CA. Axial deformation was measured with a compressometer. The results are plotted in Figure 4(a). The average unconfined strength is about 37.0 MPa. The initial modulus and the strain at peak stress are reasonably good matches to full-scale concrete of that strength. Additional test specimens were made to measure



Figure 2. Properties of steel rods used to model rebar at 1/18 scale.



Figure 3. Approximation to ERDC FACM.

the tensile strength of the model concrete. These were 14-in.-long by 2-in.-square unreinforced beams, tested in three- point bending on a 12-in. span. They were cast in rectangular forms, vibrated in the same manner as the concrete in the structural model, and troweled off along the

top surface. The tests were performed by Applied Materials & Engineering, Oakland, CA. The modulus of rupture in the three beams tested were 5.55, 5.61 and 5.74 MPa (5.63 MPa average). Companion 7.6 cm diameter compression cylinders made with the beams tested at 33.6, 36.3, and 37.9 MPa (35.9 MPa average) which is consistent with the other compression test results.



During fabrication of the structural model, 3 to 5 test cylinders were made with each batch of model concrete. Some of these cylinders were tested in unconfined compression at the time of the centrifuge tests. The age of the cylinders ranged from 251 to 364 days at that time. Figure 4(b) shows how the strength data correlate with structural component and story. As has been our experience in other concrete structures modeling programs, variations in the strength of the model concrete are caused by variations in placement and vibration, especially as they affect the consolidation of the fresh concrete. Figure 4(c) illustrates the correlation between strength and density for this set of samples. The fact that some column sections were cut out of the structure for the centrifuge tests allowed a rare opportunity to estimate the density of the model concrete in the structure from measurements. Based on measured masses and volumes of the column sections from the 1st story averaged 2.089 gram/cm3 and the section from the 4th story was 2.055 gram/cm3. Using the relation shown in 4(c), these densities indicate that the model concrete in the structure was in the range 34.5 to 37.9 MPa.

# CONSTRUCTION

The basic approach for construction was to build the structural model from the ground up, one story at time. For each story, the formwork for all the columns, beams, and floor slabs was first assembled into a single unit and positioned accurately and supported firmly. Then the steel reinforcement for the columns was emplaced, followed by the steel reinforcement for the beams and, finally, the steel reinforcement for the floor slabs. Figure 5 shows the formwork assembled during emplacement of the 1st story column steel—the outer beam side forms are not in place. The assembled formwork was supported with adjustable screw jacks under each slab plate, which in turn rested on customized steel scaffolding that spanned the aluminum table. The formwork was made of aluminum bars and plates that were nickel coated to prevent corrosion and reaction with the cement.



Figure 5. 1st story formwork assembled and supported on scaffolding over the foundation unit.

Two vertical laser beams mounted above the assembly area were used to accurately locate each floor in the horizontal plane. These shone on small countersink divots at the center of two slab plates. By aligning each story with the lasers, leaning and twist of the structure was prohibited. Level and vertical position were controlled by the jacking screws under the slab plates. Once the form assembly was in the correct position, it was secured with camping screws on the scaffolding.

Column rebar cages were prefabricated using specially designed tooling. The stirrups were very lightly spot-welded to the main reinforcing bars as necessary to hold the cage together. Both ends of each column stirrup wrapped around one of the main bars and extended through the concrete cover region to center the cage inside the form. With the exception of the 1st-story columns, the rebar cages spliced into the cages from the story below.

After all the column cages were in place, the beam steel was installed. Partial assemblies of beam steel were also prefabricated with special tooling. The lower bars were attached to stirrups that were open at the top. The upper bars were attached together with similar horizontal wires to

both assist in handling and to space them in the form. These upper bar units were placed into the opening of the stirrups, then the stirrups were bent around the outer two bars. Figure 6 shows some of the column and beam rebar during fabrication of the 1st story.



Figure 6. Beam and column rebar.

The lower rebar mats for the floor slabs were prefabricated with special tooling. They were spot welded at each intersection. A few glass beads were slipped onto some of the wires to provide the proper spacing of the mat from the bottom form. The mat dropped into the forms after the lower beam steel was placed but before the upper beam steel was placed. The upper slab rebar was also spot welded lightly to a crossing wire near each end. The ends of the upper bars were bent downward at 90 degrees to space themselves up from the form. These prefabricated units were then dropped over the upper beam steel. Figure 7 shows photographs of the concrete placement in the 1st story. The concrete was left to harden for about a week before the forms were removed, cleaned, and reassembled for the next story.



(c) Floor slabs (d) Finishing Figure 7. Model concrete placement in the 1st story.

After construction, the structure aged for about 6 months. Prior to shipping to the centrifuge facility for testing, surface flaws in the concrete were patched and many measurements were made to document the precision of the structural dimensions. Finally, the structure was spraypainted white to enhance the visibility of cracks that would occur in the tests. The finished structure and test set-up are illustrated in Figure 8.



(a) Four-story reinforced concrete structure (b) Bracket mount for high speed camera Figure 8. 1/18-scale structure on the centrifuge platform.

## EXPERIMENTS

In a realistic scenario that might cause progressive collapse, large explosive devices near one or more 1<sup>st</sup>-story columns would blast the columns and cause them to shear, bend, buckle, or otherwise lose their capacity to support the structure. Both the blast and the column response produce complex loads on the structure near the column. The present study of progressive collapse was not concerned with this part of the problem, instead focusing on the response of the structure on only the sudden removal of the support provided by one or more columns. Thus, a test requirement was to remove columns very quickly and with as little disturbance as possible to the rest of the structure.

A Reynolds RP-87 detonator and explosive was attached end-on to the side of the column with a large rubber bottle-stopper for containment. At 18 g, the detonator was initiated and the glass shattered. A fiberglass skirt was used to partially contain the blast and glass fragments.

The weight of non-structural items such as windows, utilities, equipment, storage, and people was added to the structural model to achieve the desired loading conditions. The specified level was 372.04 Pa (at 18-g). This was accomplished by placing canvas bags filled with steel shot on the floor slabs of the structure. Each bag was filled with enough #3 steel shot (3.56 cm diameter) so that with its reinforcing nylon strap and fasteners it weighed 2 kg. One bag was placed in each quadrant of a slab, positioned to place the weight partly on the middle portion of the neighboring

beam and partly on the slab. In total, 48 bags were added to each story for a total of about 386 kg (18 x 386 kg at 18 g).

In all the centrifuge tests, acceleration was measured on the top story and on the foundation with Endevco 2262 CA piezoresistive accelerometers. Deflections of the structure were measured at various locations with laser-based displacement sensors, Banner model L-Q50. These gauges use triangulation to determine the distance to a reflected laser spot on the moving target, with a resolution of about 0.38 mm and a cut-off frequency of 112 Hz (-3 db). Vertical deflection measurements were made by mounting the displacement sensors on the foundation, pointing up to the bottom of the 1st story and, by mounting on horizontal supports above the structure, pointing down to the top of the 4th story. Lateral deflections were made by mounting the sensors on aluminum bars spaced away from the structure.

Four tests were performed. Test 1 was a quasi-static loading of the intact structure under the weight of the shot-filled canvas bags at 18 g. Following Test 1, the structure was inspected for cracks. Some cracks were found on the bottom of the floor slabs. No cracks were found in the beams. The shot-filled bags were removed only from two bays on the 1st story but no cracks were seen on the top of those slabs. Test 2, the structure was loaded to 18 g and a single 1st-story column was removed while under load. When the glass replacement column was shattered, the unsupported span deflected downward about 4.76 mm. In the high-speed video of the experiment (1800 frames/sec) the displacement of the structure is visible and one or two oscillations can be tracked. Residual deflection was about 1.59 mm. Posttest inspection of the structure identified new cracks in the slabs and beams, especially in the vicinity of the removed column. In Test 3, two additional columns were removed, the column at the south east corner and the column next to it on the east end of the structure. Test 3 is described in detail below. Test 4 was a quasi-static loading of two 4th-story slabs with an exterior column pre-removed. It was performed on the north side of the structure where little or no damage occurred in the previous tests. The structure was accelerated gradually to a peak of about 33 g, at which point the failure of the 2-slab, 3beam loaded region was rather sudden.

#### Test 3

In Test 3, two columns were removed while the structure was under the 18-g load. One column was at the south east corner (adjacent to the location of the column removed previously in Test 2) and the other was next to it on the east end of the structure. Thus, the bay at the south east corner of the structure was supported by only one interior column, and the penultimate bays on the south side and east end were each supported by one exterior column and two interior columns.

Test 3 resulted in the collapse of the south east corner of the structure. The high-speed video viewing the east end of the structure captured the event quite well. Selected frames are shown in

Figure 10. All stories of the corner bay initially fell straight down and hinges formed at both ends of the beams in the middle bay of the east end. The corner column stub bottomed out first, at which time the outer beams in the 1st and 4th stories cracked in the middle of the span, followed shortly by cracking in the middle of the 2nd and 3rd story beams in the middle bay. Then the penultimate column stub bottomed out, causing the concrete in the beam-column connections above it to fail in compression. All the outer beams except the 1st-story middle bay cracked in the middle, but the hinges at the right end of the middle bay did not immediately separate from the rest of the structure so each story of the collapsing section rotated about those hinges, eventually bottoming out and/or impacting the side of the third bay. The 1st-story beam of the middle bay eventually gave way when the stories above it collapsed onto it, cracking in the middle like the others. Meanwhile, the stable portion of the structure swayed, first toward the collapsing corner, then away from it.

The deflection measurements are plotted in Figure 11. The 4th-story corner floor slab (MN5) and two of the beams that were monitored (MN1 and MN3) fell at about the same rate. The exterior beam (MN3) arrested briefly when the columns bottomed out but then deflected further when the beam broke. The gauge under the beam in the standing region of the structure (MN2) showed no significant deflection until shortly after the time that the column bottomed out, and the signal after that is almost surely due to debris crossing the path of the laser (that beam was not deflected posttest and floor slab debris was leaning against it). The interior floor slab (MN4) did not deflect. The lateral motion of the north east corner (MN7) was initially toward the collapsing corner, by about 12.7 mm, 25.4 mm, then and began to return at about the time the rotating slabs banged into the standing structure.



Figure 10. High-speed video frames from Test 3.

The collapsed portion of the structure was removed, story by story. The threaded steel rods in the beams adjoining the penultimate columns were fractured at the columns, but steel rods through many interior beam-column joints were still continuous. Some of the beam and floor slab steel was unbroken at the edge connected to the remaining structure. Some of the lower rebar mat in the floor slabs pulled out at the beams but broke in tension in the middle of the slab. The upper rebar mats in the slabs generally peeled out at the beams but some broke at the beams. Some steel bars were cut in order to clear the debris.

The half-slabs hanging to the structure were also cut away. Subsequently, all the shot-filled bags were removed so that the slabs could be inspected for cracks. Typical cracks on the top slab surface are shown in Figure 12. Rough measurements of slab center deflections were made with a 0.25 mm grid scale and a straight edge set along diagonals. These measurements ranged from 0 to 1.78 mm with a slight bias of lower deflections toward the top of the structure and away from the collapsed portion.



Figure 11. Test 3 deflections.



Figure 12. Status of structure after Test 3.

## SUMMARY AND CONCLUSIONS

This effort demonstrated the feasibility of constructing and testing a free-standing, multistory, multi-bay reinforced-concrete moment-frame structure at 1/18-scale, particularly for studying progressive collapse. The building was designed according to design codes. Threaded steel rods were used to model #9 and #11 reinforcing bars, and masonry sand was used in the model concrete. Scaled gravitational loading was provided with the centrifuge, and column removal under load was achieved with a very small amount of explosive.

The structural responses observed in the tests were consistent with expectation. Pretest computational predictions and comparisons with data will be presented elsewhere.

#### REFERENCES

- Harris, H. G, G. M. Sabnis, and R. N. White (1966), "Small-Scale Direct Models of Reinforced and Prestressed Concrete Structures," Department of Structural Engineering, Cornell U., Report No. 326.
- Harris, H. G. (Ed.) (1980), Dynamic Modeling of Concrete Structures, ACI Publication No. 73.
- White, R. N. (Ed.), "Models for Concrete Structures," ACI Publication No. 24, American Concrete Institute, Detroit, MI (1970).
- Harris, H. G. and G. M. Sabnis, Structural Modeling and Experimental Techniques, CRC Press, Washington, D.C. (1999).
- Carpenter, J. E. (Ed.), "Models of Concrete Structures," ACI Committee 444, American Concrete Institute Annual Convention, Dallas, TX (1972).
- Mirza, S (Ed.), "Structural Concrete Models, A State of the Art Report," McGill University, Montreal, Quebec (1972).
- Gran, J. K., J. R. Bruce, and J. D. Colton, "Scale Modeling of Buried Reinforced Concrete Structures under Air-Blast Loading," in Dynamic Modeling of Concrete Structures, H. G. Harris, ed., ACI Publication SP-73, pp. 125-142 (1982).
- Gran, J. K., and P. E. Senseny, "Compression Bending of Scale-Model Reinforced Concrete Walls," ASCE Journal of Engineering Mechanics, Vol. 122, No 7., pp. 660-668 (July 1996).
- Erin M. Williams, Stephen A. Akers, and Paul A. Reed, "Laboratory Characterization of Fine Aggregate Cementitious Material," ERDC/GSL TR-05-16, July 2005.