JMAT

Journal of Advanced and High-Performance Materials
for the building and infrastructure community

An official publication of the National Institute of Building Sciences
Advanced Materials Council

Winter 2011

The Next Wave of Innovation

Contents

JMAT

Published for:
The National Institute of Building Sciences
Advanced Materials Council
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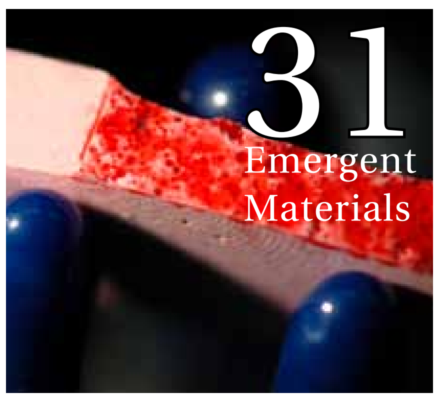

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On the cover:

The challenge facing researchers will be to develop advanced materials that will protect buildings from natural and manmade disasters while allowing designers to meet aesthetic, energy performance and sustainability goals.

Carbon Fiber-Reinforced Polymer Strengthening for Alternate Load Paths to Mitigate Progressive Collapse Vulnerabilities

New tests being conducted are showing that innovative FRP composites have the potential to strengthen structures. What will this mean for the buildings of the future?

By Zachery I. Smith and Edward R. Fyfe, Fyfe Company

IN THE PAST FIFTEEN YEARS, FIBER-reinforced polymers (FRP) have been used successfully to add considerable blast-resisting capacity to a number of structural elements (for example, columns, walls and slabs). Until recently, the testing of single degree of freedom validation and use of FRPs for force protection has been focused on local component enhancement. Whether this included adding flexural capacity to slabs for uplift pressures, increasing shear capacity in bearing columns or adding flexural capacity to CMU walls for out-of-plane induced blast pressures, it was not focused on global structural enhancement.

Progressive collapse retrofit studies take a wider view of the structure. As defined by the U.S. General Services Administration (GSA), progressive collapse is "a situation where local failure of a primary structural component leads to the collapse of adjoining members which, in turn, leads to additional collapse. Hence, the total damage is disproportionate to the original cause."

This article looks at new testing and recently completed projects that use FRP composites in combination with innovative FRP composite anchors to establish continuity at beam-column connections, improving catenary action in the event a vertical component is lost. This retrofit scheme reduces the potential for progressive collapse and could be the best design solution for retrofitting existing structures vulnerable to failure because of the as-built reinforcement discontinuities. More importantly, this work broadens the scope of influence of FRP composites from local component strengthening in years past to more global structural strengthening through alternate load paths and/or structural redundancy.

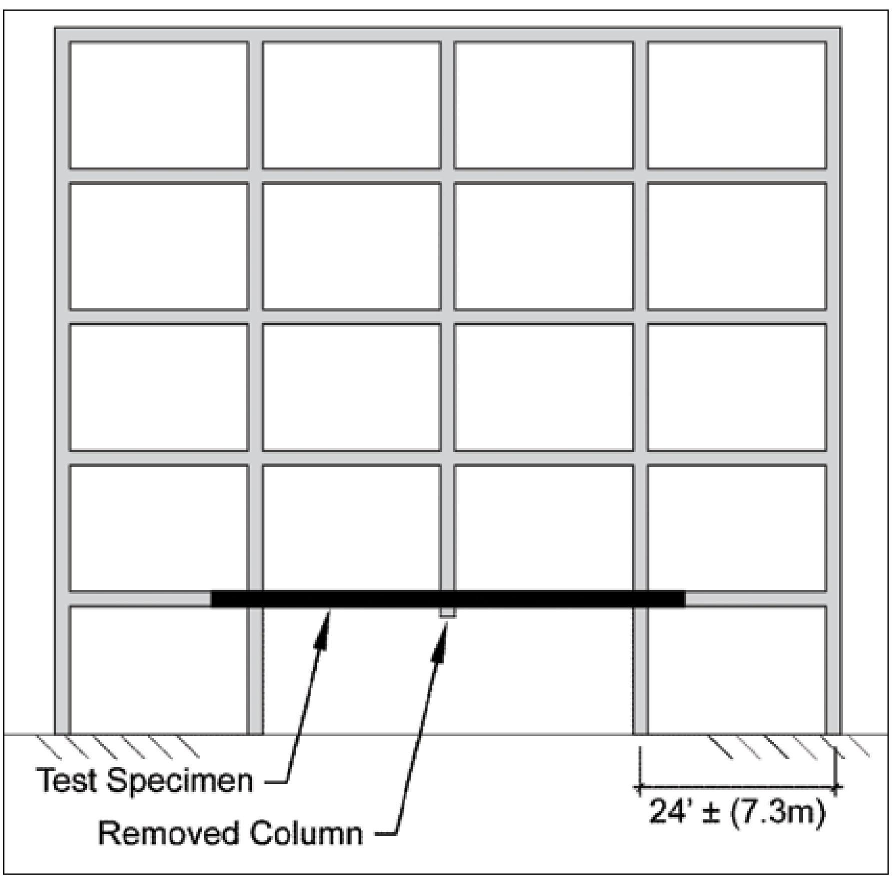

Figure 1. A building elevation with column removed.

PROGRESSIVE COLLAPSE – THE CHALLENGE

Progressive collapse presents several challenges for the engineering community. Statistically, there is a low probability of it occurring, while, at the same time, the disproportional potential damage cannot be marginalized. Unlike seismic excitation and other natural phenomena, there is not a statistical return period and magnitude of the event. This limits assessing the risk with progressive collapse to the single parameter of the greatest estimated potential damage.

As stated by the Unified Facilities Criteria (UFC 4-023-03), "the risk assessment reduces to a consideration of consequences." The risk is primarily measured in the potential human casualties. ASCE 7 outlines two approaches to mitigate the potential for progressive collapse: direct design and indirect design. Analyzing future or existing buildings by either method is a rigorous but simple engineering exercise. The testing and applications discussed in this article will focus on the alternate load path procedure.

With new construction, there are several conventional steps that an engineer can take to add structural integrity to a new building. The real challenge comes from engineering structural retrofits for existing reinforced concrete and masonry structures. Trying to add redundancy with conventional materials via alternate load paths to cross over failed vertical components in existing buildings, without adding significant structural members and impeding usable space or aesthetics, is challenging to say the least. Reinforced concrete buildings and masonry structures have similar vulnerabilities, in that their discontinuities make them susceptible to progressive collapse. The lack of continuity of the bottom reinforcement at the beam-column connection (reinforcement cutoff) makes them especially vulnerable.

THE TEST PROGRAM

The test program evaluated seven reinforced concrete beams with discontinuous reinforcement at pseudo beam-column connections to simulate a double-span scenario in which a column is lost in a blast event (FIGURE 1). The objective was to find the most effective scheme to retrofit an existing beam to support loads from a double-span case. The test sample included six beams with a variety of carbon-fiber reinforced polymer (CFRP) retrofit schemes and a control specimen. To resist progressive collapse by way of the alternate load path method, GSA guidelines require that a structure must survive a load of 2x (dead load + 0.25 live load) applied in the tributary area surrounding the lost load-bearing member. The factor of two on the structural loads tries to capture the inherent dynamic loading in the event a vertical component is lost. These guidelines for dynamic loads were built into the testing procedure.

Each beam specimen was modeled after 1970s building construction standards, with discontinuity in positive moment regions at the column line, and at mid-span in the negative moment regions. Test specimens were 30 feet long with a cross section of 6 inches wide and 12 inches deep (FIGURE 2). It should be noted that these structural tests neglected any support a typical building would provide via the surrounding slab, column line above, or phenomena such as the Vierendeel truss action. Various configurations of CFRP were applied to retrofit the beams for continuity, so they could develop catenary forces. Generally, combinations included CFRP strengthening to the underside of the beams, with fiber anchors going through the stub column section for positive moment reinforcement or CFRP strengthening on the top side for negative moment strengthening.

The CFRP system used was a unidirectional primary carbon fiber reinforced polymer with a published tensile modulus of 11,900 ksi and measured per ASTM D3039 to have a tensile modulus of 12,500 ksi. The specified concrete and steel were fairly standard strengths, at 4,000 psi and 60,000 psi respectively.

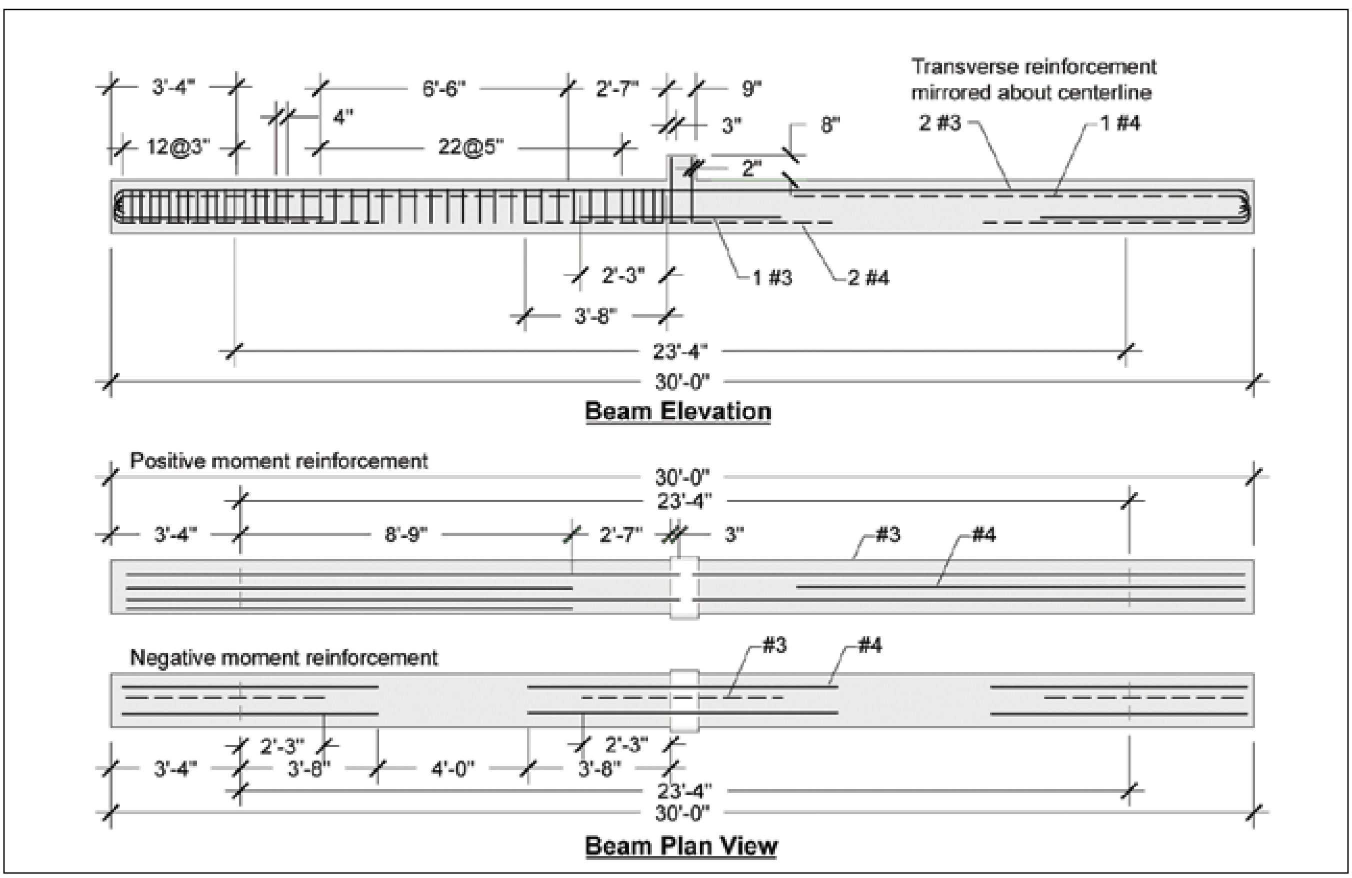

Figure 2. A test specimen.

With new construction, there are several conventional steps that an engineer can take to add structural integrity to a new building. The real challenge comes from engineering structural retrofits for existing reinforced concrete and masonry structures.

Restraints for the test specimens were provided to simulate vertical, rotational and axial factors. The end restraints provided compression and tension supports. The loading was accomplished with three loading points at mid-span and six feet on either side of mid-span. Axial resistance was also provided by a braced frame on both ends of the specimen. Note that for logistical ease the beams were inverted for testing. All specimens had instrumentation for three load cells, five displacement inducers and numerous strain gauges on the CFRP and steel reinforcing bars.

CATENARY ACTION WITH CFRP COMPOSITES FOR ALTERNATIVE LOAD PATHS

When the control specimen, NR-2, without CFRP laminates, was exposed to 23 percent of the load required for progressive collapse resistance, hinges developed at the ends and on either side of the column. As the applied load was continually increased, high deflections put the beam in catenary action, when the maximum vertical load reached 52 percent of the prescribed progressive collapse resistance. The load carried by catenary action of the existing steel reinforcement was nearly twice the load carried before the plastic hinges developed, but still half the required resistance to prevent progressive collapse.

It should be noted that the test specimens were designed to prevent a brittle shear failure, which could cause a premature failure in an actual structure **(FIGURE 3)**. However, FRP could also provide a substantial amount of shear capacity to an existing beam section to prevent such a brittle shear failure. This was not the intent of the test program, since FRP's ability to add beam shear capacity has been demonstrated numerous times in the past.

The retrofitted specimens can be divided into two categories, those strengthened in the positive moment region and those strengthened in the negative moment region. Both retrofit schemes have the same objective—to develop catenary forces.

POSITIVE MOMENT RETROFITS

Positive moment retrofits used CFRP laminates in combination with fiber anchors to establish continuity through the column section. A hole was drilled through the column section to pass through a large carbon fiber anchor that would splay out onto the CFRP laminates applied to the bottom of the beams **(FIGURE 4)**. This retrofit was designed with ductility by ensuring the steel would yield prior to the CFRP laminate fracturing. In addition to the large carbon fiber anchor passing through the column section, smaller carbon fiber anchors were used to enhance the bond interface of the laminates to prevent a premature failure from debonding.

The positive moment retrofitted specimens reached 55 and 60 percent of the prescribed resistance to prevent progressive collapse. One explanation for these specimens not meeting a 100 percent of the prescribed resistance stems from their limited rotational capacity. The concrete sections with limited rotational capacity can fracture the steel reinforcing bars before catenary action can be realized. Thus,

Figure 3. The development of a CFRP system to provide continuity in existing reinforced concrete buildings vulnerable to progressive collapse. Image courtesy of Orton, S.L.

the enhanced progressive collapse with CFRP in the positive moment regions may only be accomplished if the designer ensures that the rotational ductility in the concrete section is sufficient to reach catenary action.

NEGATIVE MOMENT RETROFITS

The negative moment retrofits are simpler logistically because they do not require developing the carbon fiber anchor through the column section as with the positive moment retrofits (FIGURE 5). The testing also showed that since the CFRP laminates are developing the negative steel reinforcement, they allowed hinges to form away from the sections with limited rotational ductility and avoided fracturing the steel rebar before catenary action was realized.

Hence, this proved to be the most successful retrofit strategy for reaching the prescribed progressive collapse resistance with one specimen reaching 108 percent of the progressive collapse resistance target. We'd like to clarify that for this test program, the summary percentages refer to the strength provided relative to total resistance needed to prevent progressive collapse per GSA guidelines.

CASE STUDY

In the winter of 2009, a U.S. Army barracks required a complete renovation, which included structural issues related to anti-terrorism/force protection (AT/FP) requirements. To satisfy the progressive collapse resistance requirements, in case the building lost a masonry pier, the engineer-of-record selected the alternate load path design method, which would strengthen the exterior masonry beams to take up the added loads. Thus, the existing masonry beams had to be designed and strengthened to span a length that is twice the span length of the original design (FIGURE 6).

This was accomplished by adding CFRP composites in the negative and positive bending regions of the masonry beams (FIGURE 7). Logistical constraints forced the CFRP composites to be designed to the sides of the masonry beams rather than the bottom of the beams. The positive moment demand was fairly minor in comparison to the negative bending demand. This design used a flexural strengthening retrofit as opposed to relying on the CFRP composite to develop catenary action. The project is a great example of global strengthening as opposed to simply local component strengthening. Traditionally, an FRP composite on this project would have been limited to strengthening walls locally for out-of-plane pressures and possibly spall control. Here the scope of the CFRP composites was broadened to strengthen the entire structure to withstand a threat through added structural redundancy versus trying to strengthen one component against local failure.

CONCLUSIONS

The research that has been completed thus far has shown that CFRP composites can successfully change load

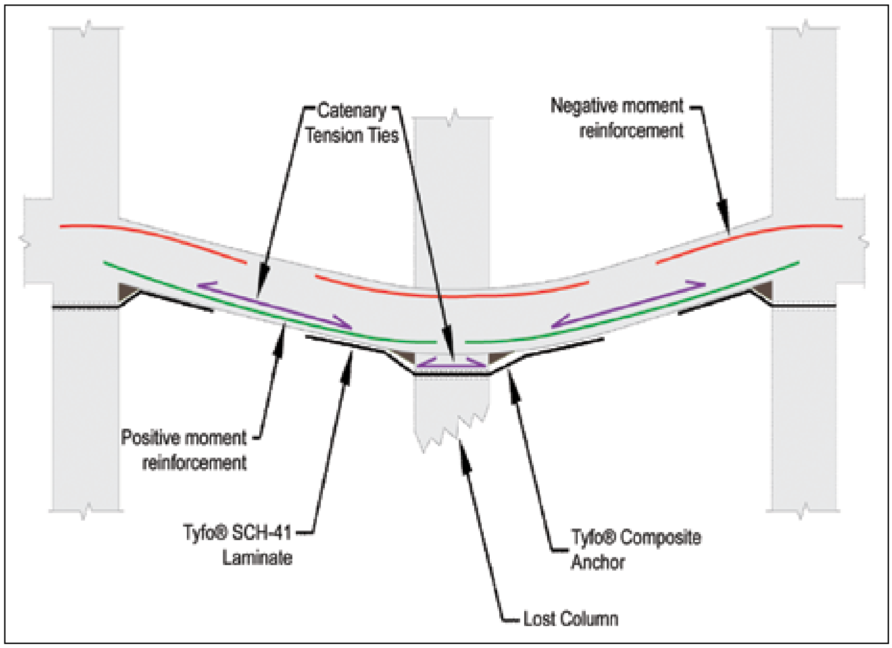

Figure 4. CFRP composites in the positive moment region to develop catenary forces.

Figure 5. Carbon anchor through stub column. Image courtesy of Orton, S.L.

paths in existing structures and reduce their vulnerability to progressive collapse. This can be accomplished in two ways: by adding continuity to induce catenary action or by enhancing flexural capacity of the beam sections. To realize catenary action in an existing structure, the designer can either retrofit the positive or negative moment regions with CFRP composites to allow plastic hinges to form when a vertical component is lost. However, the designer is cautioned that the application of this methodology in the positive moment region is constrained by rotational ductility of the concrete section, which must be sufficient to support catenary forces.

Further, load paths can be altered without realizing catenary forces, which can offer higher performance levels with lower deflections, but require substantially more CFRP composites. This method is recommended where post-event serviceability may be required (for example, hospitals) or with more brittle structural components, such as masonry beams that have limited rotational ductility. Whether a designer uses CFRPs for enhanced flexural capacity or to induce catenary action, load paths can be successfully changed in existing structures—adding a needed alternative to the retrofit options for resisting progressive collapse. ■

This paper presents summary results from Dr. Sarah Orton's PhD dissertation. Fyfe Co. greatly appreciates the continued research and support offered by Dr. Orton. Fyfe Co. donated the materials for this test program, while funding came from the National Science Foundation. For a complete study of the results summarized, see PhD dissertation by Orton (2007).

Zachery I. Smith, P.E., serves as the vice president of government services for the Fyfe Company, developing blast mitigation and force protection solutions for a wide variety of projects.

Edward R. Fyfe is the president and founder of Fyfe Co. and a leading pioneer in the FRP strengthening industry.

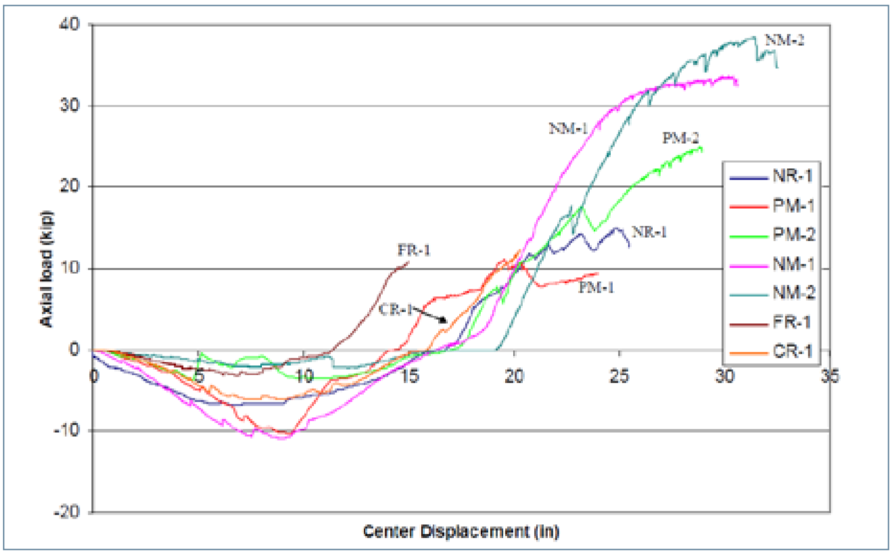

Figure 6. Axial load versus displacement. Image courtesy of Orton, S.L.

Figure 7. CFRP composite on a masonry structure for alternate load paths.

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