Avoiding Structural Failures During Construction

Part 2

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Structures are most vulnerable when they are in the process of being constructed or renovated. Part 1 of this series of articles (STRUCTURE®, November 2007) dealt with failures due to premature formwork removal, poor bracing assumptions for compression members, and lack of engineering altogether. This article will deal with failures of permanent structures. It will present engineering principles and "lessons learned" that can be used by design professionals, owners, and construction managers to minimize the probability of these unfortunate events.

The Straw that Broke the Camel's Back

Making a penetration in a non-loadbearing wall should be a routine operation. So why did it cause bricks to rain down onto Madison Avenue during the holiday shopping season?

540 Madison Avenue in New York, NY is a 38-story office building that was built in the early 1970s. The building structure has a reinforced concrete frame and a brick facade. The façade consists of brick veneer supported on relieving angles on every floor. Each relieving angle has a horizontal soft joint underneath and a course of lip brick on top. The back-up for the brick is a non-loadbearing wall of cinder concrete masonry units (CMU), and, in the area of the elevators and stairs, the backup is a reinforced concrete shearwall.

Figure 1: 540 Madison Avenue, partial facade collapse. Courtesy Channel 7 News.

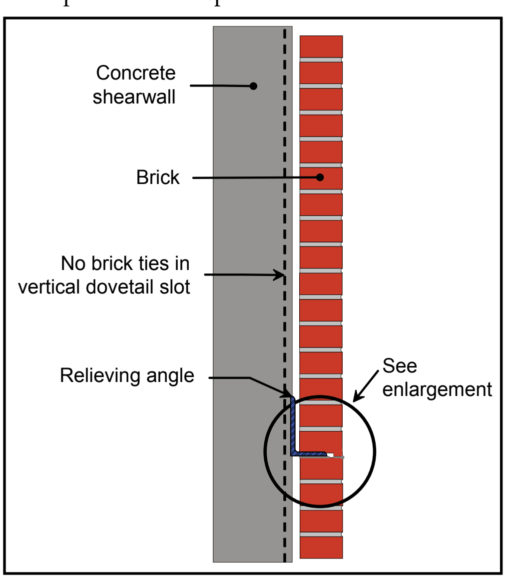

Figure 2a: 540 Madison Avenue wall section: The failure was caused by a combination of lack of brick ties and excessive compression in the brick due to non-functioning horizontal soft joints. The soft joints were not wide enough to accommodate shortening of the concrete frame and moisture expansion of the brick.

In 1997, a building-wide renovation project was initiated. This renovation included adding windows to the south wall, which is over a low building. The windows were small, about 3-feet, 6-inches square, and there were typically three per floor. The window penetrations were made through the brick veneer and through the CMU backup.

On a Sunday afternoon, December 7, 1997, a portion of the south wall from the 35th floor collapsed, raining bricks down onto the low adjacent building and onto Madison Ave. The incident resulted in the closing of many stores between 54th and 55th Streets during the holiday shopping season, and hobbling traffic along a major midtown artery. *Figure 1* shows an overall view of the façade after the failure.

Fortunately, there was plenty of warning prior to the failure. About six months prior to the collapse, an engineer observed from a scaffold that the bricks at the 35th floor were displaced. Apparently, the condition that existed at that time was not yet alarming, so the engineer recommended further study. A month before the collapse, the condition had become alarming. A large bulge had developed, which was estimated to be as large as 12 inches deep, 60 feet wide, and 10 feet high. Emergency measures were immediately undertaken to protect the areas below, and to attempt to stabilize the bulging brick. A swing scaffold was positioned directly beneath the unstable area as part of the protection. These measures mitigated the damage.

So, why did this failure occur? For two reasons, as illustrated in *Figures 2a and 2b*. First, the field investigation revealed that brick ties were completely missing over large expanses of the wall. The vertical dovetail slots in the concrete shearwall were filled with fiberglass insulation and concrete, clearly indicating that brick ties had never been installed. About 60% of the façade had this condition. In these areas, the 4-inch thick brick veneer was essentially balanced on its edge with no lateral support. This condition had existed since the day the wall was built.

The second reason was that the brick veneer was subjected to high compressive stresses. These high stresses were caused by the inability of the horizontal soft joints to accommodate the natural expansion and contraction of the building. These dimensional changes were produced by two cumulative effects: 1) creep and shrinkage of the concrete frame, a phenomenon that structural engineers learn about in undergraduate courses, and 2) the natural expansion of the brick due to moisture absorption, which structural engineers may not be familiar with. That the joints had been squeezed closed was clearly visible in portions of the façade that had not collapsed. Since the majority of creep, shrinkage, and moisture expansion occur early in the life of the structure, this condition also had probably existed for many years and went undetected.

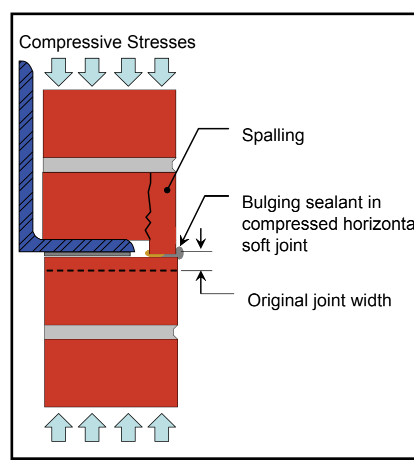

Figure 2b: Visual inspection can detect symptoms that a wall is being unduly compressed, such as brick spalling and bulging of sealant. With lip brick, as shown above, micro-probes are needed to determine the remaining width of the joint under the angle.

So, what triggered this event to occur at the moment that it did? It was probably the making of the window openings. The introduction of openings reduced the net section of wall, thereby increasing the already high compressive stresses in the wall. Although this renovation work, in and of itself, should not have caused any problems…it was the straw that broke the camel's back.

This event has a number of lessons for us. One is that periodic façade inspections should include ALL sides of the building. Prior to this event, New York City required that only facades over sidewalks needed to be inspected. The façade that fell, therefore, was exempt from inspection. Within months, the law was modified to require that all sides of a building be periodically inspected. This incident also underscores the importance of inspection during construction. Even the most rudimentary spot check during construction would have detected the brick ties were not being installed. And, finally, this incident reinforces the fact that inspections of existing facades by qualified professionals can often detect problems before they occur. The bulging sealant and the spalling of the brick along the relieving angles were telltale signs to an engineer familiar with masonry facades that the brick might be under high compression, and that further investigation was needed on an expedited basis. Such an investigation would have probably resulted in the recommendation that new horizontal soft joints be installed prior to cutting the window openings, and it probably would have detected the missing brick ties.

Lateral Torsional Buckling

This topic is important for several reasons. For one, a failure that occurs due to lateral torsional buckling tends to occur suddenly, without much advance warning. This increases the potential for casualties and fatalities. Secondly, this failure mode is not necessarily intuitively obvious to all parties involved in a project. In certain situations, even experienced structural engineers may not recognize this vulnerability. This topic is of particular importance in the construction phase, since some of the elements that would have provided bracing in the completed structure may not yet be in place or be fully effective.

Two case studies help illustrate very different scenarios. One scenario occurs relatively frequently in certain building types and has resulted in a number of fatalities cumulatively, and the other scenario is the unusual case of a fatal bridge collapse that triggered changes in the governing codes.

C-Joists Floor Framing

Take the situation of light-gage metal joists (C-joists) supporting floor loads, which is common in low-rise residential construction. It may seem obvious to a structural engineer that the deck should be positively attached to the supporting joists before any additional load is applied. After all, most engineers understand that the bending strength of certain shapes, such as C-joists, is highly dependant on the compression flange being properly braced. If the flange is unbraced, it will buckle laterally, about the weak axis of the member. This is highlighted by the typical note in the manufacturer's joist span table, which says, "Spans are based on continuous lateral support of the compression flange." The design drawings typically specify the fasteners, which, in the completed structure, will provide more than adequate bracing. However, the design drawings usually will not address stability of the joists during erection, since this is properly part of the contractor's means and methods.

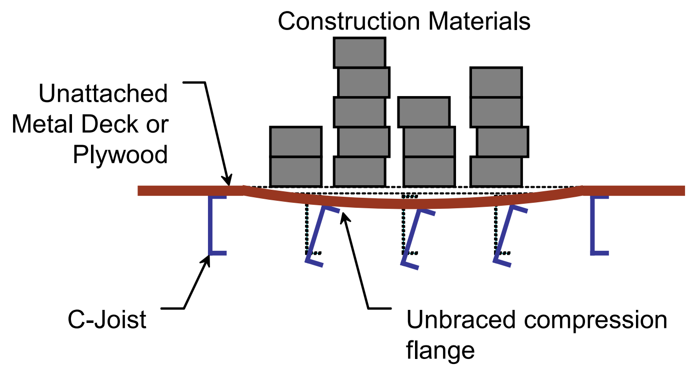

Figure 3: Light gage metal joists are vulnerable to lateral torsional buckling if their compression flange is not properly braced. Contractors may not be aware of the importance of attaching decking before loading a floor.

But the importance of immediately attaching the deck to the joists may not be obvious to the contractor. It is not uncommon for a contractor to construct temporary work platforms that serve as staging areas for construction material. The contractor may simply lay the decking on the light gage joists and begin loading it with construction materials, with the intention of making the permanent attachments later. What the contractor doesn't realize is that the joists are dramatically weaker if the deck is not attached to them. If subjected to modest loads, the joists will fail due to lateral torsional buckling, as illustrated in *Figure 3*.

These cases highlight the need to communicate to contractors the importance of providing bracing for C-Joists. This can be done via notes on the design drawings and comments on the shop drawings, in a manner that does not negate the contractor's responsibility for means and methods. The light gage metal joist industry can reduce the likelihood of these types of failures by providing prominent warnings in its literature and on its packaging.

Marcy Bridge Collapse

An unusual case of lateral torsional buckling is that of the Marcy Bridge. One reason that it is unusual is because, contrary to "conventional structural wisdom," lateral

Figure 4: The Marcy Pedestrian Bridge following collapse during placement of the concrete deck.

torsional buckling occurred about the strong axis of the bridge section.

Composite steel and concrete structures often require special bracing during construction to ensure stability before full composite action can be achieved. This is particularly true for composite box girder bridges, which consist of open top steel tub girders that can be susceptible to lateral-torsional buckling under construction loads prior to curing of the concrete deck. The collapse of the Marcy Bridge in upstate New York, during construction in October 2002, illustrates the importance of considering constructability in composite steel and concrete design.

The Marcy Bridge was a pedestrian bridge designed to span approximately 170 feet across an extension of the Utica-Rome expressway (NYS Route 49) in Marcy, New York. The design consisted of a single trapezoidal steel tub girder with a composite reinforced concrete deck. The bridge was straight in plan, and arched in elevation. The bridge collapsed during casting of the deck, shortly after placement of the wet concrete had passed midspan, severely injuring nine workers and killing one. The failure mode was determined to be lateral-torsional buckling of the steel tub girder in which the entire girder cross-section participated, not simply the compression flanges. A photograph of the collapsed tub girder is shown in *Figure 4* and the buckled shape computed by the structural analysis software, ABAQUS, is depicted in *Figure 5*.

Prior to and during placement of the concrete deck, the tub girder was an open section and was therefore relatively flexible torsionally. After curing, the concrete deck would have created a closed cross section, and the increased torsional stiffness would have prevented lateral-torsional buckling. Torsional stiffness can be increased prior to placement of the slab by means of a top flange lateral bracing system to create a quasi-closed section. However, top flange lateral bracing was not prescribed in the design or included in the fabrication of the Marcy Bridge. Another means by which a closed cross section can be created is through adequately designed stay-in-place formwork. While the Marcy Bridge utilized stay-in-place forms, the connections between the individual panels were not engineered for this purpose and therefore could not prevent the lateral-torsional buckling from taking place.

Although the open tub girder was torsionally flexible, global lateral-torsional buckling was unexpected because the tub girder was straight and it was being loaded about its minor axis. The potential for lateral-torsional instability of horizontally curved tub girders is clear, since torsional loads exist simply due to self weight and the curved shape. As such, it is common for bridge engineers to include top flange lateral bracing in the design of horizontally curved tub girders. In fact, a composite box girder construction manual published by the United States Steel Corporation states, "Properly designed curved box girders should include lateral bracing and internal diaphragms as part of the design." (See *Steel/Concrete Composite Box-Girder Bridges, A Construction Manual*, United States Steel Corporation, 1978.)

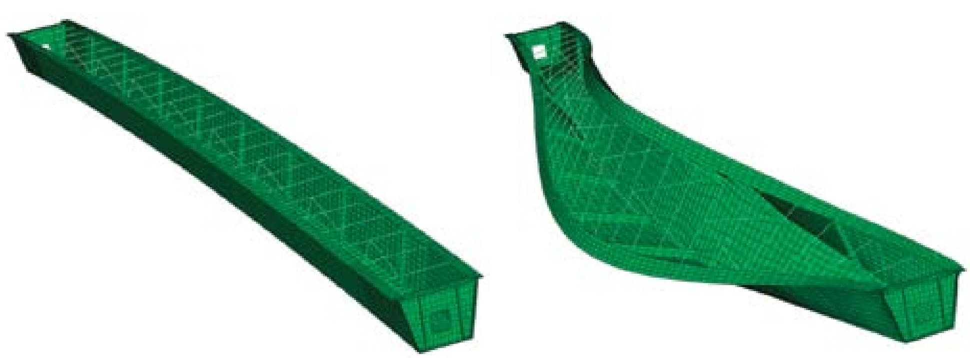

Figure 5: Finite element model of the Marcy Pedestrian Bridge showing the undeformed shape and the global lateral-torsional buckling mode.

In contrast, the potential for lateral-torsional instability of horizontally straight tub girders is not as obvious. However, if one considers that the shear center of the tub girder is located below the tub girder cross sections, it becomes more evident that eccentricities in construction loads can generate torsional loads in the torsionally flexible open section. The same US Steel *Construction Manual* states, "Experience has shown that, for construction, it is also advisable to use a full-length top lateral system, either temporary or permanent, in straight box girder bridges having spans greater than 150 feet."

Despite the recommendation of the US Steel document and other literature, top flange lateral bracing was not an explicit requirement of the 16th Edition of the AASHTO Standard Specifications for Highway Bridges adopted by New York State at the time of the design of the Marcy Bridge. Additionally, lack of clarity in the Specifications regarding lateral bracing may have misled the design engineers to believe that internal diaphragms and struts could function as bracing against lateral-torsional buckling rather than just control warping distortion of the steel tub girder.

The flexibility of the open cross section without lateral bracing, coupled with the vertical curve and long, slender geometry, made the Marcy Pedestrian Bridge susceptible to lateral-torsional buckling.

A lesson that can be learned from the Marcy Bridge collapse is that a thorough consideration of all possible limit states of a design should be made, in addition to those that may be addressed in codes. Limit states that affect constructability of the structure are particularly important. As an outcome of the collapse, New York State Department of Transportation issued an Engineering Bulletin in July 2003 requiring full length lateral bracing systems for all tub girders that rely upon a composite concrete deck to form a closed cross section.

Conclusion

Two of the three cases discussed in this article directly prompted revisions to governing codes and standards: the partial collapse of a façade resulted in changes in the inspection requirements at the local level, and the collapse of a bridge triggered design changes at the state level. Code provisions can be an effective way to capture the lessons learned from a failure, particularly for those situations that are within the control of the design professional, or where enforcement is likely. For the other case, of the bracing of C-joists, code changes would not be effective, since the contractor would likely not be aware of the provisions and the local authority would likely not be able to enforce it. In this case, the most effective approach may be to educate and inform those individuals who have control of the work, or who are performing the work, through trade organizations, safety training, or manufacturer's packaging information.▪

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