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Structural Redundancy Inherent with Masonry

By David T. Biggs, P.E.

Figure 1: Pentagon September 11, 2001

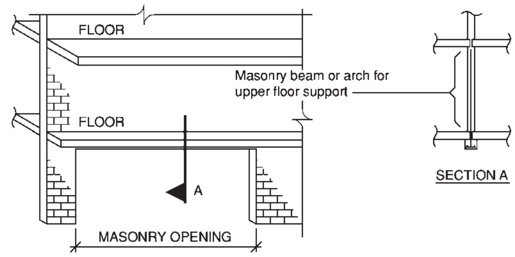


Figure 2: Wall beam and arching

Structural redundancy provides alternate load paths, added strength or added stiffness. These enhancements, often not considered in design, each contribute to improving structural safety during abnormal loading events. Why do we need such redundancy? Terrorist activity has led to public demand for heightened security in all areas of society, including building safety. Redundancy is also beneficial during an unforeseen accident.

Do not confuse structural redundancy with overdesign. Redundancy occurs by the nature of the structural system and detailing of the elements, not simply by adding more structure. Non-structural building elements can perform added duty for structural purposes. Structural elements often have greater capacity than assumed during design. For instance, fire–rated column enclosures can be detailed to add stiffness to the structure, reduce drift and provide increased axial load capacity in the event of a connection failure of the beams and girders. This will be illustrated later.

Recent events highlight the beneficial effects of redundancy and the need to prevent progressive collapse. The Alfred P. Murrah Federal Building bombing in Oklahoma City on April 19, 1995 and the events of September 11, 2001 are terrorist cases where greater structural redundancy would have been useful. Redundant behavior would be beneficial in saving lives and saving buildings in the case of accidental gas explosions, subsurface movement, non-specific explosions (blast) and vehicle impact.

While structural redundancy applies to all types of construction, masonry has the ability to improve structural safety and performance both locally and system-wide. Local redundancy is particularly useful during accidental events. System-wide use of redundancy is generally required to prevent progressive collapse. Government design standards have been proposed to prevent progressive collapse of federal buildings. Designers may follow these standards for non-governmental buildings where greater occupant safety is desired.

While redundant masonry features enhance performance during abnormal or extreme loading events, they can also reduce the cost of non-masonry elements. Using masonry to its full capacity, design masonry to function as both loadbearing and shear walls. In a frame building where masonry is used to enclose space, structural characteristics are not fully utilized. Have we forgotten that partition walls still have structural capacity? Masonry can reduce the cost of the frame and add redundancy with little or no additional cost.

Framed structures, introduced in the late 1800s, replaced loadbearing masonry as a predominant system. Originally, the systems blended. Masonry was used for partitions, enclosures and to fireproof columns, beams and girders. Masonry was even used for floor systems. As partition walls have been built with lighter, less expensive materials, the inherent redundancy of masonry has been lost. Perhaps it's time to reconsider that approach.

Redundancy can be used whether or not designers specifically address progressive collapse. Here are examples of some localized enhancements.

Masonry Openings

Lintels or headers usually span openings in masonry walls; many older buildings have masonry arches. Arching action is inherent in masonry. During extreme events, it is ready to act and has been effective in preventing accidental collapse from explosions, car impact and sinkholes. *Figure 1* is taken from the Pentagon attack where aircraft debris penetrated to the third ring of the building and created the opening in the lowest floor of the five-story building. Arching action in combination with the structural frame prevented total collapse of the wall.

In multi-story masonry buildings, supplemental steel or concrete elements often span large openings; in this case, arching action provides redundancy. However, masonry can be detailed as an arch or beam, minimizing supplemental framing or eliminating it altogether (*Figure 2*). Arching action can provide either redundancy or greater economy.

Column Enclosures

Many architects enclose steel columns with masonry to develop a fire rating. *Figure 3* shows a typical detail from the National Concrete Masonry Association.

These details allow space between the masonry and the column but this is not required. *Figure 4* shows how the detail can be modified to provide structural redundancy by encasing the column rather than just enclosing it; brick encasement could be used also. The fire-rating remains; masonry effectively increases both compressive and flexural strength of the building column.

With adequate anchoring to the column, masonry encasement can be treated compositely with steel. Added strength provides redundant column strength, or it can be used to increase column stiffness to resist seismic or wind loads. If encasement is reinforced, it can minimize strain-induced tension cracking of the composite section.

Figure 5 shows masonry encasement providing added strength during an extreme event. It is one of several columns damaged in buildings at the World Trade Center disaster. Frame collapse may have occurred without this redundancy.

Infill Walls for Building Frames

Building masonry walls tight to the underside of framing provides redundancy. They provide an alternate load path in the event of beam or girder damage or connection overload. This has been observed in fire-damaged buildings.

Masonry infill walls have not been codified in the United States for their shear capacity. However, research has indicated that these walls provide reliable performance during in-plane loadings. This has been known intuitively for years. In the early 1900s, many frame buildings under 100' tall were designed for only gravity loads knowing the masonry walls, both interior and exterior, provided significant lateral load resistance without resorting to calculations.

The Masonry Standards Joint Committee (MSJC) *Building Code Requirements for Masonry Structures* (ACI 530/ASCE 5/ TMS 402) recommends that walls be isolated from a frame to prevent drift-induced cracking

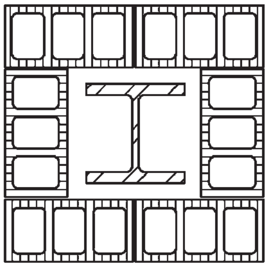


Figure 3. Fire-rated steel column

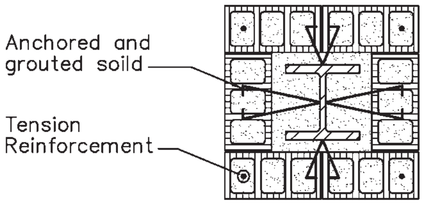


Figure 4: Structural redundancy of fire-rated column

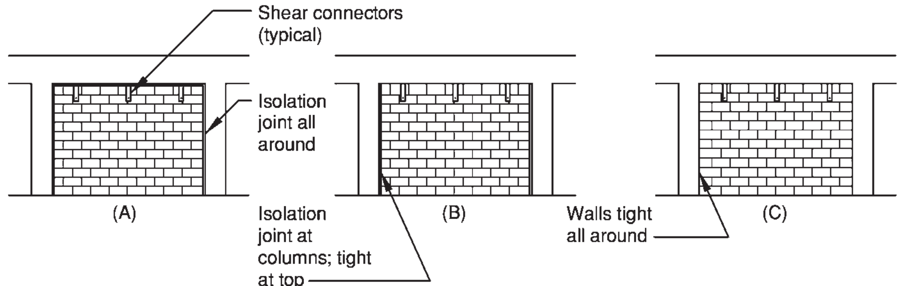


Figure 6. Infill walls

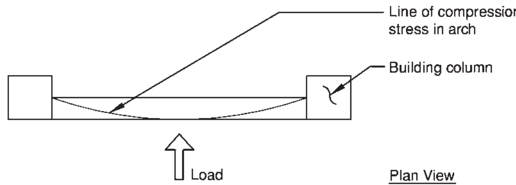


Figure 7: Out-of-plane arching action

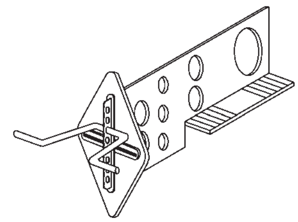


Figure 8: Composite wall tie

because code provisions to account for wall stiffness and strength are not completed; this is conservative. Until provisions are developed, engineers may use their own judgment on design methodologies. For redundancy and greater building strength, there are conceptually three methods for using the strength of masonry more efficiently (*Figure 6*).

The first method anchors the wall for out-of-plane loads, yet allows drift. Top anchors slip to avoid vertically loading the wall but impart shear into the top of the wall (*Figure 6a*). This is consistent with current MSJC recommendations as long as there is a soft joint that allows column drift without bearing on the edge of the wall. The wall can be designed for out-of-plane effects as well as in-plane shear.

The second method is similar except the wall is constructed tight to columns which transfer shear into the wall (*Figure 6b*) through edge bearing rather than relying upon top connections. There are no MSJC provisions for this method.

The third method is to build masonry tight to columns and beams (*Figure 6c*). Again, there is no MSJC procedure. There have been many research papers published on this method verifying that a diagonal compression strut develops. The vertical load on the wall also increases the shear wall capacity.

Figure 5: Column encasement preventing collapse

Constructing all edges of the wall tight to framing also engages arching action for out-of-plane loads and provides multiple levels of redundancy (*Figure 7*).

The third method offers potential savings in the frame as well. Beams and girders can be designed only for gravity loads prior to installation of the wall. With this method, what appears to be masonry infill is actually a bearing wall and a shear wall. The wall should be adequately marked so it is not removed or modified by renovations.

Hopefully, MSJC will address each of these methods and increase the efficiency of the infill wall.

Cavity Wall Strength

Cavity walls use adjustable ties. The veneer is non-structural; the backup (masonry, concrete, wood or cold-formed metal) provides the flexural (out-of-plane) strength. It is possible to distribute the lateral load between the veneer and backup based upon their relative stiffnesses. This provides a natural redundancy making the backup design conservative.

Many older masonry walls were constructed compositely with veneer and backup rigidly anchored. Where the collar joint between wythes is fully grouted, the wall functions compositely. Where the collar joint is a cavity, the wall may or may not function compositely; it is dependent upon the ties. Horizontal joint reinforcement does not provide the required stiffness needed across the cavity to create composite action. However, there are cavity wall ties on the market that create composite action (*Figure 8*).

Designers should be cautioned against using composite walls in geographical regions where mortar deteriorates by weathering or freeze-thaw. Structural integrity may be lost if exterior mortar deteriorates. It is prudent to use added strength for redundancy, not for basic design.

A second caution with composite walls is to use materials that are compatible for movement. CMU veneer is compatible with CMU backup because they will respond similarly to temperature changes and have similar shrinkage characteristics. Brick veneer may not be sufficiently compatible with CMU backup since the irreversible moisture growth of the brick opposes the shrinkage of the CMU. If brick veneer is to be used compositely with CMU, it is recommended to use brick that has been exposed to weather for up to a year so that the moisture growth occurs prior to wall construction.

Subsurface Movement

Older brick buildings were often constructed with inverted arches in the foundation walls. The arches distributed column loads into subsurface soils. Though inverted arches are not used in modern construction, they could be used to provide redundancy against subsurface settlement by redistributing loads.

Progressive Collapse

Extending structural redundancy to a system-wide approach provides for protection against progressive collapse. In the commentary of American Society of Civil Engineers (ASCE) Standard 7-02 *Minimum Design Loads for Buildings and Other Structures*, progressive collapse is described as "the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it." This is a major concern because significant structural damage and fatalities can occur.

The British have developed progressive collapse methodology from experience with building collapses during World War II and terrorists activities. While ASCE 7 indicates intent, the United States has no design methodology for progressive collapse in building codes. The Department of Defense (DOD) developed a draft standard that is

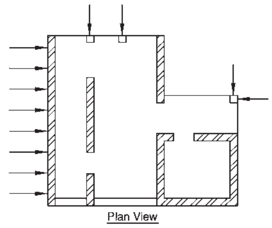


Figure 9: External horizontal ties

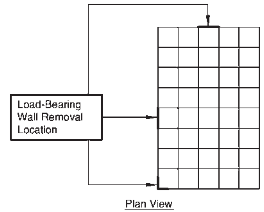


Figure 10: Mandatory locations for removals for alternate path method

derived from British standards and must be used for all Department facilities. In all likelihood, the private sector will use the same standards until a consensus document is developed.

While the standard applies to concrete, structural steel, masonry, wood and cold-formed steel structures, this article discusses masonry structures. Refer to the standard for an in-depth review of topics.

Planning for progressive collapse requires system-wide redundancy. The overall concept is that structural elements be tied together so that loss of support in one area does not propagate and cause collapse of a *disproportionate* amount of the structure. (Some have recommended that progressive collapse be renamed as disproportionate collapse.) In the past 10 years, the Murrah office building, the World Trade Center (WTC) towers and WTC 7 did not resist progressive collapse.

For new construction, the design procedure is based upon a desired level of protection. Each structure is categorized as Very Low, Low, Medium or High in terms of needed protection. Structures are analyzed and designed to meet two strategies called Tie Forces and Alternate Path.

Tie Forces

For the Very Low protection category, this strategy is to connect structural elements with horizontal ties. For the Low, Medium and High protection categories, the strategy connects elements with both horizontal and vertical ties. In the context of progressive collapse, ties are structural elements that provide continuity and ductility to the structure. Horizontal ties consist of reinforcement anchored or *tied back* to walls, beams or columns to each floor or roof. Horizontal ties are required at the periphery of floors and roof, including reentrant corners, internally for floors and walls and externally for columns and walls (Figure 9). Vertical ties consist of continuous reinforcement from the foundation to the roof.

Ties must be continuous and be anchored at the ends; they are made using the same reinforcement designed for other purposes. The DOD standard gives design forces for these ties.

A major consideration is that all reinforcement splices for ties must achieve full capacity of the reinforcement through welding or mechanical splices; lap splices are not allowed. This is different from the MSJC, which requires welded or mechanical splices to achieve 125% of the yield strength of the reinforcement.

Alternate Path

There must be an alternate load path when critical elements are removed in all structures in the Medium and High protection categories. Alternate load paths are also needed whenever it is not possible to develop vertical tie force in elements. The acceptance criteria is that a structure must be able to both bridge over an element that is removed in the analysis and meet a level of performance.

Analyses are based upon strength provisions of the 2002 MSJC using loading combination 1.0D + 0.5L + 0.2W; no live load reductions are allowed. The strength reduction factor, Φ, is 0.8 for shear and 1.0 for axial and flexure.

A three-dimensional model is required for these analyses using static procedures (linear or non-linear). Dynamic analysis is discouraged due to the possible variables and complexity.

Multiple analyses are required since each analysis removes only one element. That one element could be either one of the locations where the vertical tie strength can't be achieved or one of the three mandatory locations for each floor. *Figure 10* shows mandatory locations for removals in loadbearing walls; each location must be analyzed for each floor. This produces a large number of calculations.

Near the middle and side of the building, removal length is the greater of two times the wall height being removed or the distance between movement (control or expansion) joints. At corners, the removal length in each direction is equal to the greater of the wall height being removed or the distance between movement joints. These removal lengths may be reduced to the length of wall between vertical intersecting elements that are loadbearing and connected to the wall being removed.

The ability to span over the removal area of wall elements is natural for masonry due to arching action and the ability to create wall beams. The greatest challenge will occur with walls with numerous openings.

Minimum Requirements

Masonry design minimum requirements to meet the progressive collapse standard:

- Minimum thickness (solid wall or one loadbearing wythe) = 150mm (6″).
- Minimum characteristic compressive strength = 5N/mm (approximately f'_m = 725 psi).
- Maximum h/t = 20.
- Allowable mortar = Type N or S.
- Exterior wall: Minimum percentage of reinforcement = 0.05%.

There was no discussion in the standard as to how these limits were set and why Type M mortar was not included. This may be an oversight in the transference from British standards.

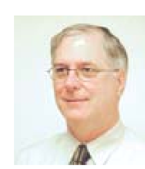
The h/t criteria will limit heights of many tall wall projects. The f'_m requirement should not be a problem for new construction since many projects typically use at least f'_m=1500 psi.

Detailing

The DOD standard notes that typical seismic detailing can be used. However, welded or mechanical reinforcement splices are required for ties. Sample details are included from a specific text.

Masonry construction has many beneficial features that can provide redundancy either inherently or if appropriately detailed. Most features do not increase construction cost; they use masonry more efficiently. Only infill walls require new design techniques.

Many construction features that address progressive collapse are already typical for seismic designs. Added effort is required to create splice details for ties and to develop the structural analyses for the Alternate Path strategy.



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