# Performance of Concrete Masonry Buildings in the Joplin Tornado

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## 1. INTRODUCTION

On May 22, 2011, a large and violent tornado struck southern portions of Joplin, MO. According to the National Oceanic and Atmospheric Administration (NOAA, 2011), the tornado killed 158 people and injured more than 1000 people. The tornado was rated EF-5 on the Enhanced Fujita Scale, with maximum winds exceeding 89 $ms^{-1}$ (200 mph). During the week following the tornado, the author conducted aerial and ground surveys of the damage. Surveying the damage was a challenge due to the large numbers of damaged or destroyed buildings (about 8,500 structures) as well as the rapid clean-up that was ongoing. Certain buildings were being demolished with heavy equipment within days after the tornado. Therefore, the author decided to select a sample of 14 buildings constructed with concrete masonry unit (CMU) walls.

CMU buildings typically had a combination of load-bearing walls (grouted cells reinforced with steel rebar) and non load-bearing walls (no grouted cells or rebar). Walls typically failed along horizontal lines or joints at their bases or in line with consecutive window sills. Similar masonry wall failures were documented by Marshall et al. (2008) after the Greensburg, KS tornado. In Joplin, failure of load-bearing walls occurred frequently where the wall rebar lapped the foundation rebar. Loss of the load-bearing wall(s) usually led to partial or total collapse of the roof. Failure wind speeds were obtained from the EF-scale study by the Wind Science and Engineering Center (WSEC, 2006). It was determined that such wall failures occurred mostly in the range of EF-2 to EF-3 winds or in the range of 56 to 67 $ms^{-1}$ (125 to 150 mph).

## 2. CONCRETE MASONRY WALLS

Concrete masonry units are cast in molds by mixing Portland cement, aggregate, and water. Individual units are formed with hollow cells to aid hydration and reduce weight. The units are cured in special drying chambers. Mortar bonds the stacked CMUs together. Mortar is a mixture of Portland cement, lime, sand, and water. A common pattern for laying masonry is a "running bond" where each successive course is offset half its length.

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CMU walls can be load bearing. That is, walls support dead loads (i.e. weight of the roof and roof structure) as well as live loads (i.e. snow, wind, etc.). Steel rebar is inserted into cells in the CMU, and the cells are filled with grout. Grout is a watered down version of mortar (usually without the lime added) with the consistency of slurry. The slurry needs to fill the cells without any voids. For there to be a continuous load path, rebar extends from the foundation and laps the wall rebar in the same cells, in the lowest courses of the walls (Fig. 1). Building codes do not require the lapping rebar to be tied together. Wall rebar extends vertically up to a bond beam that has continuous horizontal rebar in consecutively grouted cells. Bond beams are typically one course tall and grout is prevented from filling empty cells below by a mesh-type grout stop material placed in the bed joint underneath the bond beam. Sometimes U-shaped CMU are used. Building codes do not require that the wall rebar be tied to the bond beam rebar. Roof trusses typically are strapped or welded to steel plates embedded within the bond beam (Fig. 2).

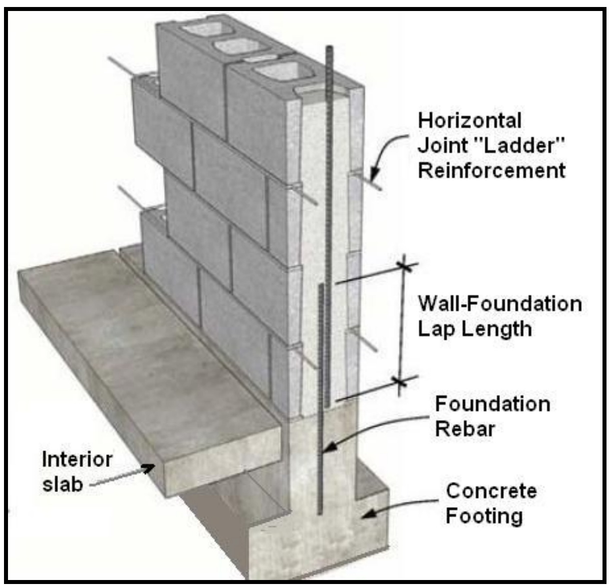


Figure 1. Typical cross section of the base of a load-bearing CMU wall showing rebar placement in vertically grouted cells. Spacing of vertical reinforcement along the wall depends on the size of the wall and design loads.

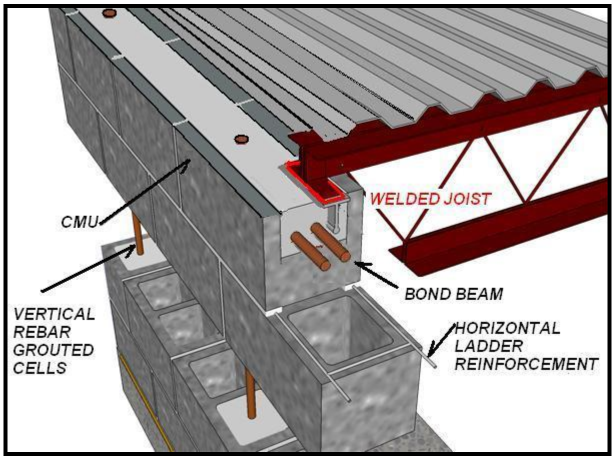


Figure 2. Typical cross section at the top of a load-bearing CMU wall showing rebar placement, the grouted bond beam, and the attachment of a roof truss to the bond beam.

The basic design wind speed for Joplin, MO is a three-second gust of 40 $ms^{-1}$ (90 mph) at 10 m (33 ft) above the ground. Building codes do not include the design for tornadoes. Thus, buildings with CMU walls are particularly vulnerable to catastrophic failure as wind loads increase beyond the design load. In general, the higher and wider the wall, the greater the overall wind load, and the greater the probability of wall failure.

## 3. SELECTED CMU BUILDINGS

A total of 14 CMU buildings in the tornado path were selected for detailed examination (Fig. 3). The tornado intensified rapidly as it entered southwest portions of Joplin, first striking a residential area before traveling east-northeast through the medical district where St. Johns hospital was located. The tornado destroyed a number of doctor's offices before striking the hospital. Among the buildings examined, were a pair of two-story medical buildings constructed with CMU perimeter walls. These buildings were in the center of the tornado path. Both buildings collapsed when load-bearing CMU walls failed.

Next, the tornado continued east-northeastward destroying St. Mary's Church, the Fellowship Hall, and school, and then heavily damaged a nearby Bowling Alley. Within the next mile, four adjacent CMU structures were impacted including Joplin High School, Franklin Technology Center, Harmony Heights Baptist Church, and the Church of Jesus Christ. The tornado then struck a major commercial district along Range Line Road where there was a heavy concentration of CMU buildings. The author examined the Walmart, a gas station, Walgreens, and Cummins Equipment buildings among others. The easternmost CMU building examined by the author was the East Joplin Middle School. Eight of the 14 buildings are discussed in this paper.

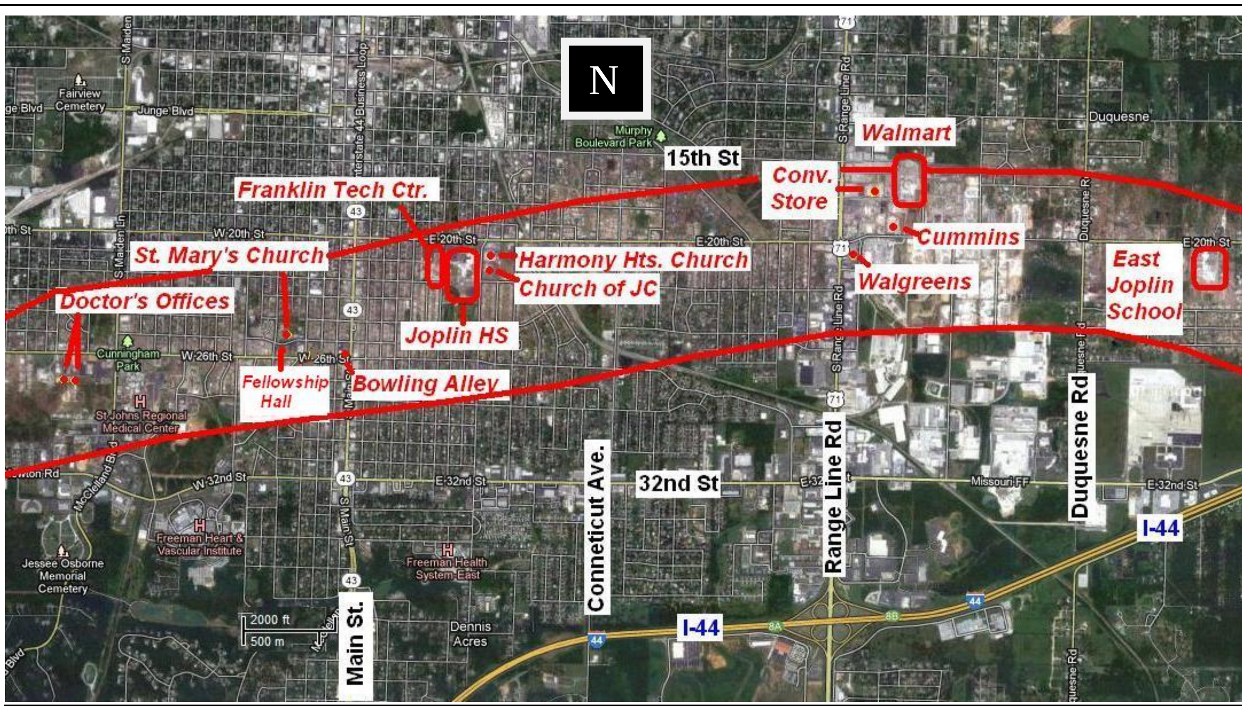


Figure 3. Path of the Joplin tornado along with the locations of the inspected CMU buildings. The damage path averaged 1 km wide.

3a. St. Mary's Church/School

St. Mary's Church/School was in the middle of the tornado damage path. The building had a two-story sanctuary on the west end and a one-story school that extended east from the sanctuary. The center of the tornado passed directly over the building. South walls fell to the north, east walls fell to the east, north walls fell to the south, and some of the steel beams that supported the sanctuary roof, were transported west across Moffet Ave. The carport structure on the south side of the building remained intact along with the steel cross (Fig. 4).

The sanctuary was a steel-framed structure with non load-bearing perimeter walls consisting of CMU interior and exterior brick veneer. There was no air space between the CMU and brick. Steel columns fell into the sanctuary pulling apart bolts that connected their base plates to the concrete slab foundation. Non load-bearing masonry walls fell inward, pivoting about bases of the walls. Close examination revealed no vertical reinforcement between the walls and the slab foundation (Fig. 5). The walls essentially were unanchored.

In the school portion of the building, load-bearing CMU walls were aligned north-south, whereas non-load-bearing walls extended east-west. As typical with schools, classrooms had large arrays of glass windows. Windows were in the non load-bearing north and south walls. There were masonry columns, about 1.5 m wide, between the window arrays. Since the masonry columns were not load-bearing, they did not have vertical reinforcement or grouted cells. Failure of the masonry columns occurred along horizontal lines at window sill level (Fig. 6).

Figure 4. South elevation views of St. Mary's Church before (a) and after (b) the tornado. The carport structure and cross remained, but the sanctuary and school structure collapsed. The pre-storm image was obtained from Google Earth.


Figure 5. Inward collapse of the non load-bearing masonry wall on the northwest side of the sanctuary at St. Mary's Church. The unanchored wall pivoted about its base.

Figure 6. Inward failure of the south, non load-bearing, masonry wall along a horizontal line window sill level: (a) columns outlined in red, and (b) closer view showing the absence of vertical reinforcement where columns failed.

According to the EF scale, the expected value for total destruction of a large section of an Elementary School (ES) building or entire building would be 79 $ms^{-1}$ (176 mph), with a lower bound of 68 $ms^{-1}$ (152 mph), and an upper bound of 91 $ms^{-1}$ (203 mph). Given the observed absence of vertical reinforcement within the CMU walls, with the steel carport structure remaining intact, the author selected the lower bound failure wind speed at 68 $ms^{-1}$ (152 mph) or EF-3. Five cars in parking lots near the church were moved during the tornado, but remained upright.

3b. Bowling Alley

The bowling alley was a one-story structure constructed on a concrete foundation with load-bearing east and west CMU walls. Barrel-shaped steel roof trusses were anchored to 61 cm (2 ft) thick concrete bond beams. Brick masonry veneer covered the outside perimeter of the building.

The center of the tornado passed directly over the bowling alley removing the roof covering and joists. However, steel roof trusses and the perimeter masonry walls remained intact except for a portion of the west wall that collapsed near the northwest corner apparently when struck by a truck. The northernmost truss fell when that portion of the load-bearing wall toppled (Figs. 7 and 8).

Figure 7. Southwest elevation of the bowling alley: (a) before and (b) after the tornado. Walls and trusses remained intact except at the north end of the building where a truck impacted the west wall. The pre-storm image was obtained from Google Earth.

Figure 8. Damage to the west CMU wall where a truck impacted: (a) overall view and (b) close-up view showing the thick concrete bond beam atop the CMU wall.

According to the EF-scale, the expected value for uplift and removal of the roof structure for a large, isolated, retail building (LIRB) would be 60 $ms^{-1}$ (134 mph). If not for the truck impact, the load-bearing wall and north roof truss probably would have stayed intact. Whether the degrees of damage (DOD) 5 or 6 are selected, the failure wind speed would have been in the EF-2 to EF-3 range.

3c. Franklin Technology Center

The Franklin Technology Center was a one-story structure with brick exterior and CMU interior walls. East and west walls were load bearing and supported large span, steel roof joists. Walls contained a cavity between the brick and CMU filled with insulation board. North and south walls were non load-bearing as were many of the interior partition walls. The building was located at the north end of the tornado damage path (Fig. 9). East and north walls fell inward, whereas south and west walls fell outward. Nearby trees were uprooted and fell southwest.


Figure 9. West elevation of the Franklin Technology Center: (a) before and (b) after the tornado. The building was located at the north end of the tornado damage path. The pre-storm image was obtained from Google Earth.

Close examination of the load-bearing masonry walls revealed failure occurred where the foundation rebar lapped the wall rebar, a few courses above the foundation slab surface (Fig. 10). At most, the lap was the height of one CMU, about 20 cm (8 in). The wall rebar simply pulled out of the grouted cells or became detached when the grouted cells broke. Non load-bearing CMU walls at the north and south ends of the building were not anchored to the footing and rotated inward at the slab surface.

According to the EF scale, the expected value for total destruction of a large section or an entire Elementary School (ES) building would be 79 $ms^{-1}$ (176 mph), with a lower bound of 68 $ms^{-1}$ (152 mph), and an upper bound of 91 $ms^{-1}$ (203 mph). Given the observed poor construction of the building, the author selected the lower bound failure wind speed at 68 $ms^{-1}$ (152 mph) or EF-3.

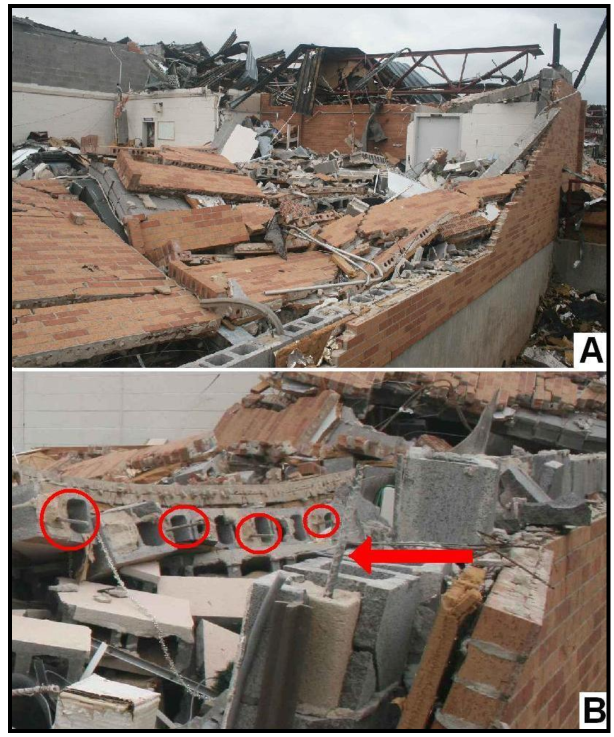


Figure 10. East load-bearing wall of the Franklin Technology Center fell into the building causing collapse of the roof: (a) overall view and (b) close-up view showing exposed wall rebar (circled) and foundation rebar (arrow).

### 3d. Joplin High School

The original Joplin High School was a cast-in-place, steel-reinforced concrete structure with exterior, non load-bearing "fill-in" CMU walls, as well as non load-bearing interior CMU partition walls. Later additions had steel framing. The gymnasium and auditorium were located at the south end of the school complex and were constructed with CMU interior and brick exterior walls. North and south walls of the gymnasium and auditorium were load-bearing, while east and west walls were not.

The High School was on the north end of the damage path and experienced the strongest winds from the north and east. A portion of the exterior north CMU wall and several interior partition walls fell into the second story hallway. This could have been tragic had these hallways been occupied during the tornado (Figs. 11 and 12).

The north load-bearing wall had fallen inward causing collapse of the roof. The south end of the non load-bearing west wall had toppled inward, and the north end fell outward. Gymnasium walls were approximately 10 m (33ft) tall (Fig. 13).

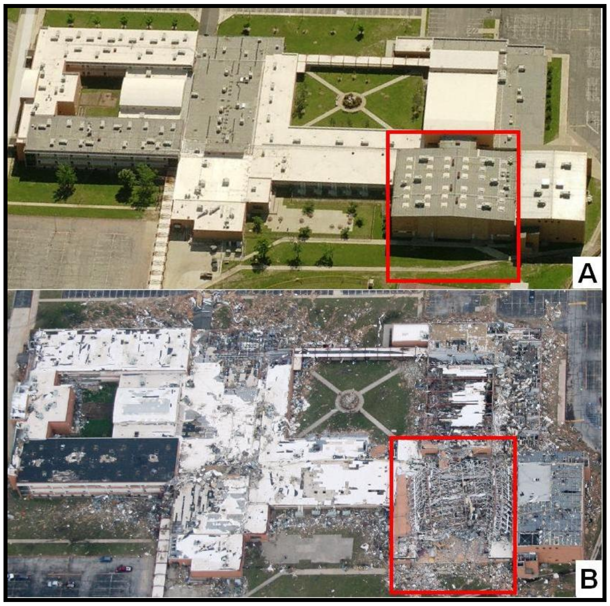

Figure 11. Aerial images of the Joplin High School looking east: (a) before and (b) after the tornado. The gymnasium (red box) collapsed. The pre-storm image was obtained from Bing.com.

Figure 12. Collapse of second story CMU walls at the Joplin High School: (a) north hallway and (b) center hallway.

Figure 13. Collapse of CMU walls at the Joplin High School Gymnasium: (a) overall view looking east, and (b) close-up of the non load-bearing west which fell inward.

According to the EF scale, the expected value for total the collapse of tall masonry walls at a gymnasium (DOD 7) would be 51 $ms^{-1}$ (114 mph) with collapse of exterior walls in the top floor being 62 $ms^{-1}$ (139 mph). The author selected the higher wind speed which is at the lower end of EF-3.

3e. Walgreens Drug Store

The Walgreens Drug Store building was a one-story structure oriented east-west. North and south CMU walls were load-bearing supporting steel trusses, whereas east and west walls were non load-bearing. An array of windows extended along north and west sides of the building; the front entrance faced northwest.

The building was in the center of the tornado damage path. The non load-bearing west wall fell inward, pivoting about the base of the wall. Positive internal pressure helped push the top of the north load-bearing wall outward, and the roof collapsed (Fig. 14).

This building was a small retail building (SRB) and the roof structure collapsed (DOD 6), along with some exterior walls (DOD 7), but the building was not totally destroyed (DOD 8). Thus, the expected failure wind speed for DOD 7 was around 62 $ms^{-1}$ (138 mph), or EF-3 on the EF-scale.


Figure 14. North elevation of the Walgreens Drug Store: (a) before and (b) after the tornado.

### 3f. Cummins Equipment

The Cummins Equipment building was a one-story, steel-framed structure constructed on a concrete foundation. Exterior, non load-bearing walls were constructed with CMUs. The long dimension of the building was oriented north-south. Large overhead bay doors faced east and there was an array of windows on the south side of the building.

The building was in the center of the tornado damage path and completely collapsed (Fig. 15). South and west walls fell into the building while north and east walls fell outward. There was no anchoring of the CMU walls to the roof structure or foundation.

This building was selected as an automobile service building (ASB) and was destroyed (DOD 8). Thus, the expected value failure wind speed was around 70 $ms^{-1}$ (157 mph) or EF-3 on the EF-scale.


Figure 15. Southeast elevation of the Cummins Equipment building: (a) before and (b) after the tornado. This steel-framed structure had non load-bearing CMU walls that collapsed during the tornado. The pre-storm image was obtained from Google Earth.

### 3g. Walmart

The Walmart building was a one-story, steel-framed structure with both load-bearing and non load-bearing CMU perimeter walls. The building was rectangular in plan with the long dimension oriented north-south; the front of the building faced east.

This building was near the northern edge of the tornado damage path. The south half of the building collapsed but the north half remained intact. East and west walls toppled into the building and the south wall fell outward. Failure of the load-bearing walls caused the roof to collapse (Fig. 16).

Close examination of the CMU walls indicated that walls failed where the foundation and wall rebar lapped. Both foundation and wall rebar pulled out of the broken grouted cells (Fig. 17).

According to the EF-scale, the expected value for the complete destruction of a large section of an LIRB building would be 77 $ms^{-1}$ (173 mph) or EF-4. Cars in the parking lot were moved, rolled, tumbled, and lofted. One vehicle was wrapped around a tree such that the frame was bent into a U-shape (Fig. 18).

Figure 16. Aerial view looking east of the Walmart building: (a) before and (b) after the tornado. The south half of the building collapsed. The pre-storm image was obtained from Bing.com.

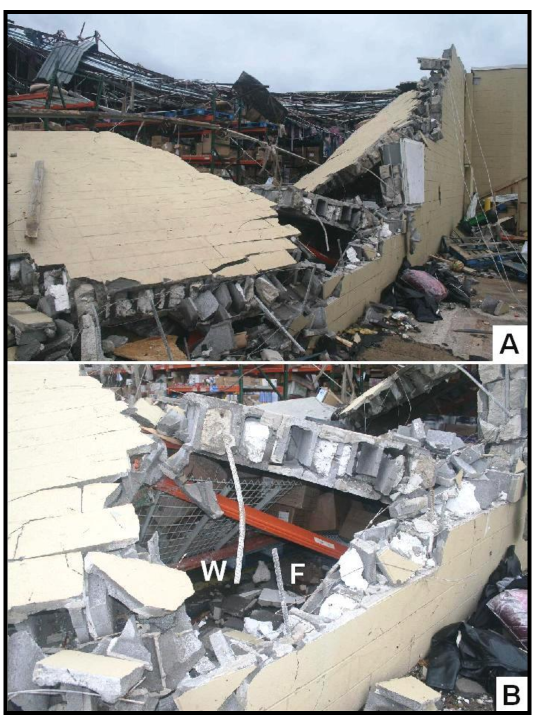

Figure 17. Inward collapse of the east wall on the Walmart building: (a) overall view and (b) close-up view. Failure occurred when wall rebar (W) pulled out of the grouted cells leaving the foundation rebar (F).


Figure 18. Four-door vehicle bent into a U-shape around a tree just south of the Walmart building.

### 3h. Joplin East Middle School

The Joplin East Middle School was constructed in 2009. Perimeter and interior walls were constructed with vertically-stacked CMU including an auditorium at the southeast corner of the school (Fig. 19). All four walls in the auditorium were load-bearing. However, the north and south walls supported curved, steel roof trusses. The CMU walls were approximately 10m (33 ft) tall.

The center of the tornado passed directly over the school. Strong west winds and positive internal pressure caused the east wall in the auditorium to fall to the east and the south wall to fall to the south, resulting in collapse of the entire roof structure. Remaining CMU walls in the school remained intact. Close examination of the toppled CMU walls in the auditorium revealed that rebar extending out of the foundation simply pulled out of grouted cells at the bases of the walls while vertical rebar in the walls were pulled apart (Fig. 20).

According to the EF scale, the expected value for the collapse of the roof structure for an Elementary School (ES) building (DOD 7) would be 56 $ms^{-1}$ (125 mph) with an upper bound of 66 $ms^{-1}$ (148 mph) and lower bound of 48 $ms^{-1}$ (108 mph). Given that collapses were confined to the two largest spans in the school, and that there was little lateral strength in the large walls, the author selected the failure wind speed at around 125 mph or EF-2.

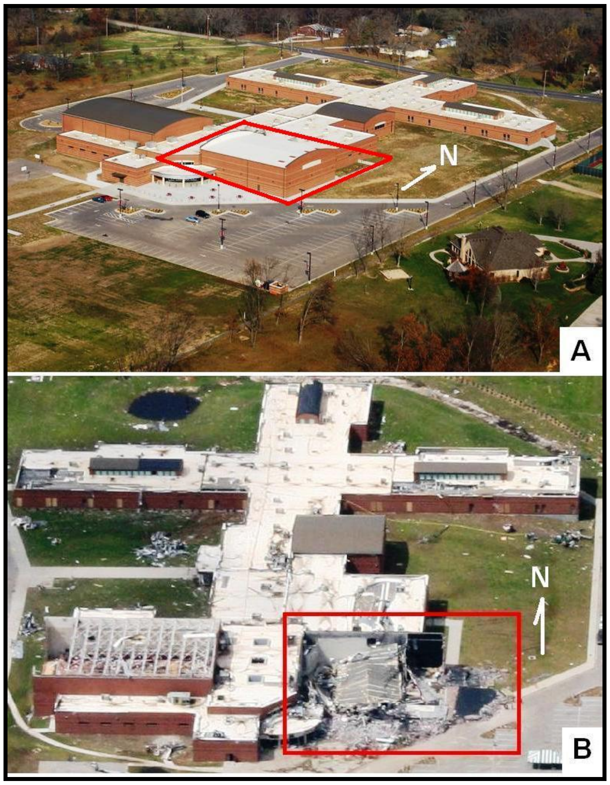


Figure 19. Aerial view of the East Joplin Middle School: (a) before and (b) after the tornado. The red outline indicates the location of the auditorium which collapsed. The pre-storm image was obtained from Bing.com.

## 4. SUMMARY

The author examined 14 damaged or destroyed buildings with CMU walls after the Joplin tornado. Damage analyses of eight of those buildings are presented in this paper. CMU walls were both load-bearing walls (grouted cells reinforced with steel rebar) and non load-bearing walls (no grouted cells or rebar). Walls typically failed along horizontal lines or joints at the bases of the walls or in line with consecutive window sills. With load-bearing walls, failure occurred typically where the wall rebar lapped the foundation rebar. Failure of the load-bearing walls led to partial or total collapse of the roofs.

In this study, it was determined that CMU wall failures occurred mostly in the EF-2 to EF-3 range on the EF-scale with failure wind speeds between 56 to 67 ms$^{-1}$ (125 to 150 mph). Analyses of other building types currently are underway and will be presented at future proceedings. Such detailed examinations of building damage will add to the data base and help determine the range of possible failure wind speeds.

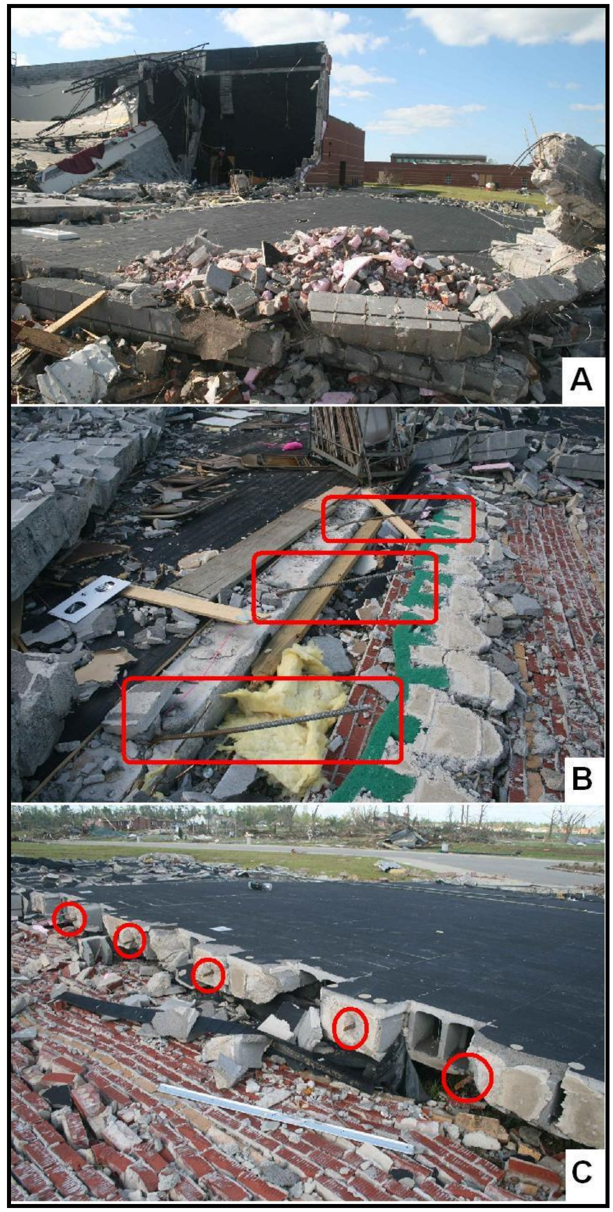


Figure 20. Details of the east wall that failed in the East Joplin Middle School auditorium: (a) overall view looking north, (b) bent foundation rebar (circled), and (c) broken rebar (circled) at the base of the east wall.

## 5. ACKOWLEDGEMENTS

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