TILT-UP CONCRETE ASSOCIATION

ANALYSIS OF DAMAGE FROM HISTORIC TORNADO IN JOPLIN, MISSOURI, U.S.A. ON MAY 22, 2011

a Report to the

TECHNICAL COMMITTEE

of the

TILT-UP CONCRETE ASSOCIATION

by the

NATURAL DISASTER TASK FORCE

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TILT-UP CONCRETE ASSOCIATION

1. EXECUTIVE SUMMARY

The May 22, 2011 EF-5, multi-vortex tornado that struck Joplin, Missouri produced damage that may approach $3 billion.[1] With a death toll of 162 people as of September 14, 2011, it was also one of the deadliest tornadoes in the country. While the damage was catastrophic to all types of construction, an article in the June 25th edition of The Kansas City Star[2] singled out Tilt-Up concrete construction for severe criticism. In particular, Tilt-Up construction was criticized for its "domino effect.". Also, comparisons to nearby big-box structures with less damage inferred that there was a unique flaw or danger in Tilt-Up construction.

The Technical Committee of the Tilt-Up Concrete Association (TCA) formed a Task Force shortly after the article was published to investigate the claims presented in the article. The article quoted many sources, but the most serious claims against Tilt-Up construction were based on comments made by Larry Tanner, an investigator with a Federal Emergency Management Association (FEMA) team. The work of the Task Force consisted of performing detailed engineering calculations, research, and investigation of the claims made in the article. The Task Force consisted of a nationwide group of practicing structural engineers with a diverse range of experience in Tilt-Up construction and big-box buildings.

The Task Force's findings to date include:

1. The failure started in the structural steel, steel joist and wide-rib deck roof system. This roof system is one of the most commonly used systems in commercial buildings, including those with masonry walls, precast concrete walls, and almost all forms of wall construction
2. The Tilt-Up concrete panels performed very well and survived the extreme loads of the EF-5 event only to collapse after the roof failed due to lack of bracing mechanism.
3. Tilt-Up construction methods played no role in the failure.
4. The perception that the nearby Wal-Mart store performed better because it was concrete masonry is false. The Wal-Mart took a glancing blow from the storm and the Home Depot took a direct hit.

The Task Force has identified five general recommendations listed in the final section of this report. These recommendations focus on increasing building safety in catastrophic storms through enhanced building performance and/or the use of shelters. The recommendations also stress the inherent strength and durability of Tilt-Up construction and recommends the TCA develop responses that take advantage of this performance. Finally, the Technical Committee should work with the Steel Deck Institute, Steel Joist Institute, National Council of Structural Engineers Associations (NCSEA), and code bodies to develop specific design and construction guidelines and recommendations for high winds. This must include more accurate information regarding the performance of deck attachment in simultaneous high uplift and shear.

2. PURPOSE AND INTRODUCTION

This report is a response to the claims made in an investigative article published in the June 25, 2011 edition of The Kansas City Star. The author of the article was Mike McGraw, a Pulitzer-Prize winning special projects reporter for The Kansas City Star. In this article, the author made a number of claims that are listed in Appendix Item 1. The principal claim is "Tilt-Up construction is deadly in certain circumstances". All other claims flow from this assertion.

The Tilt-Up Concrete Association (TCA) believes this assertion represents a poor understanding of overall building performance. Tilt-Up construction is a method of construction and not a type of building. How the walls were cast, whether in a plant or on the site, and how they were erected has nothing to do with how they perform once in-place. Furthermore, the critical opinions of the article were largely based on those of Mr. Larry Tanner of Texas Tech University. Mr. Tanner spoke freely with Mr. McGraw about his engineering opinions and he is quoted extensively in the article. Key points made in the article include:

1. "Under high winds the roof can become compromised and the panels in Tilt-Up wall buildings can fall like dominoes".
2. "...once you lose a wall panel, then the dominoes all start to fall"
3. "If the building codes had required the Home Depot store to have stronger roof-to-wall connections, it might have sustained less damage even in such heavy winds".

These statements are particularly troubling to the Task Force since the damage to all forms of construction across a wide geographic storm path was catastrophic.

It must be stressed that this Task Force of the Technical Committee of the TCA supports efforts that will lead to stronger and safer buildings. Ultimately, the purpose of this report is to move the discussion towards this goal and away from loose speculation. This report will hopefully lead to a better understanding of the performance of the Home Depot project in this catastrophic storm, and to a better overall understanding of commercial building performance in severe winds.

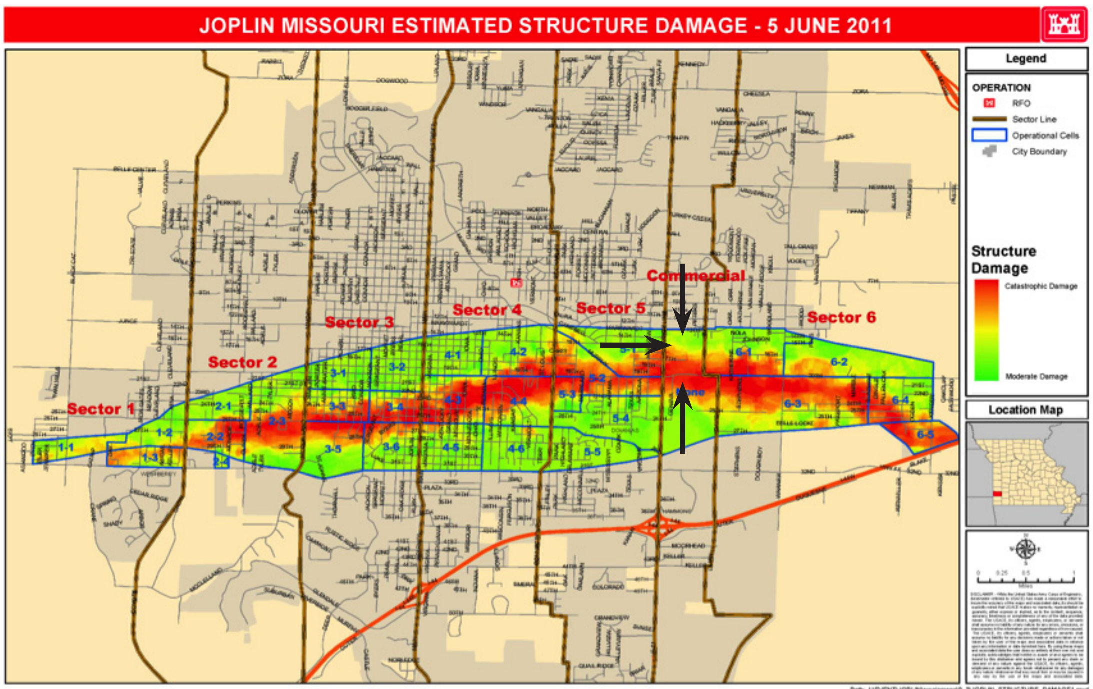

Figure 1 - U.S.A.C.E. Storm Path Damage

3. STORM EVENT DESCRIPTION AND OBSERVATIONS

The storm touched down in the Joplin area at 5:41 p.m. and traversed a path of more than 13 miles before dissipating. Six (6) full miles of the storm were within the city limits of Joplin. The maximum width of the storm was three-quarters of a mile. The initial Enhanced Fujita (EF) rating was a high end EF-4 and this later was revised to EF-5. The maximum wind speeds were in excess of two-hundred (200+) miles per hour.[6]

An early storm damage/path map from the Army Corps of Engineers is shown as Figure 1. The Home Depot is located at 3110 East 20th Street just east of South Range Line Road (U.S. Route 71). This location places the building directly in the storm path and in the area confirmed on the map as catastrophic damage. Its location is denoted as the lower arrow in Figure 1.

Figure 2 - Home Depot - Image Credit, Associated Press

The Home Depot building was a complete collapse as shown in Figure 2. It should be noted that numerous photographs show the panels survived intact and the failures of the panels and their connections to the roof system occurred as a secondary result of falling, not as a primary failure due to wind load. This is a very important distinction.

Several other big-box buildings in the same area used concrete masonry construction and were not as heavily damaged. This observation was made by Joplin Fire Chief, Mitch Randles in The Kansas City Star article. A few paragraphs later the article makes the assertion that "Some (unnamed) engineers think that concrete block structures may be safer in a collapse than Tilt-Up wall buildings." To examine these assertions, the locations of the buildings and other variables were examined.

Figure 3 - Academy Sports - Image Credit, Associated Press

The Academy Sports Building, a former K-Mart big-box store, is located at 1717 South Range Line Road. This places it just north of the Home Depot site (center, horizontal arrow in Figure 1) at the northern edge of the catastrophic zone. This building was severely damaged but lost only a portion of its roof (see Figure 3). It was noted that this building was unique in that it has had an 18-gauge roof deck (in lieu of the 22-gauge roof deck as specified on the Home Depot) according to M.A. Carter, P.E.[3] He further noted that puddle welds were used as the roof deck to structural connection and expressed an opinion that these connections performed poorly. Puddle welds are susceptible to workmanship since welders may burn through the light gauge deck, which can reduce the deck's capacity.

Figure 4 - Wal-Mart - Image Credit, Associated Press

Wal-Mart Store 59 is located at 1501 South Range Line Road, which places the store (top arrow in Figure 1) well north of the catastrophic zone. This is consistent with the thought that it took a glancing blow from the tornado vortex (Figure 4). This point was discussed in a presentation to the Structural Engineers Association of Kansas and Missouri on June 29, 2011 by insurance investigation engineer and Missouri Structural Assessment and Visual Evaluation (SAVE) Coalition volunteer, Thomas Heausler, P.E., S.E.[7] Both Figure 2 (Home Depot) and Figure 3 (Wal-Mart) show a clear absence of roof deck.

From the previous discussion, it is clear that there are at least several other key variables involved in evaluating the performance of a building and particular wall type. It is clear the biggest variable is the exact location of the structure relative to the path of the tornado. The suggestions in the article regarding the superiority of concrete masonry are very questionable when the storm path locations are examined and the variability of roof deck construction is considered.

4. ENGINEERING METHODS AND ANALYSIS

4.1 GENERAL DISCUSSION

The first step in the investigation was to obtain the cooperation of Home Depot. This was achieved and the Task Force contact was Mr. David Oshinski, the Director of Construction for Home Depot. Mr. Oshinski provided a set of structural engineering drawings for the Home Depot store in Joplin, Mo. These drawings remain the property of Home Depot. The drawings were produced by CASCO of St. Louis, Mo. Mr. Oshinski also supplied a set of photographs of the failed building taken within approximately 24 hours of the storm. Mr. Oshinski also shared the observations from interviews of managers on duty during the storm. Shop drawings or special inspection reports from the original 2000 construction were unavailable.

All buildings consist of an overall gravity and lateral system that is comprised of a number of sub-systems. The overall system used for the Home Depot has long been referred to by engineers and building codes as a Box Building System, BBS. ACI 551 describes box systems as carrying the loads through a series of planes. This is true regardless of the type of wall element that is provided; Tilt-Up concrete, precast concrete or concrete masonry. The engineering approach of the Task Force was to develop overall loadings for the structure and then examine first the various sub-systems, or planes. After this review, the overall performance in a severe wind event as a system, or BBS, was examined. The failure of any sub-system or plane in the event may or may not lead to an overall building collapse. The one exception to this statement is a complete failure of the roof diaphragm. A sudden and complete failure of this critical sub-system would lead to a complete collapse of the building. An example of a non-compromising level of performance would be a local snow-drift failure of a series of roof joists. While this is very bad, it is generally confined to a limited area and does not compromise an overall plane.

4.2 WIND LOADS

The drawings showed the building was designed for a 90 mph exposure C wind load under the 1996 BOCA Basic Building Code[9] (Note: The wind speed maps for the BOCA code indicate required wind speeds for the area of 70 mph; therefore, Home Depot exceeded the code required wind load). Wind analysis performed by the Task Force largely confirmed the wind loads shown on the Home Depot structural drawing S3.0. Further, wind analysis using the most recent International Building

Code 200910 and ASCE Standard Number 711 computations developed winds that are roughly comparable to those used in the original design. In other words, the most recent codes do not specify significantly different wind loads than those used in the original design.

4.3 GRAVITY SYSTEM

The first sub-system examined was the gravity system. A general review of the documents showed routine open-web joist and joist-girder construction. No indication of an uplift failure of the gravity interior columns was reported. Also, the girders remained largely in place after the storm, albeit virtually destroyed. It should be noted that the joist girders were not required to have an uplift design, so whether uplift braces were provided to allow for overload situations is not clear. Since a gravity failure was not relevant, no further time was spent on this system.

4.4 TILT-UP WALL PANELS

The second system examined was the load bearing Tilt-Up wall panels. These panels serve multiple purposes; as gravity load bearing walls, as lateral "out-of-plane" wind resisting elements, and as longitudinal load resisting shear-walls. The walls are critical to the proper function of a box building system and the specific material is not an issue since Tilt-Up, precast, or concrete masonry can all be designed and constructed to function properly.

Calculations performed by the Task Force indicate that the design of the Tilt-Up concrete wall reinforcing was adequate for the design wind loads required by the building code in effect at the time. Furthermore, there was no indication that any shear-wall action (racking) of the panels was ever realized in the system, so panels were not highly stressed. No further calculations of the lateral, shear resisting capacity of the tornado winds was performed since this was not the failure mode.

Finally, the only indication of failure of a critical embedded item was that provided in The Kansas City Star article. In the graphic used in the newspaper, it is implied that the winds were so strong the anchors were ripped from the walls. The Task Force requested, and was supplied, supporting photos from Mr. Wayne Lischka, P.E., the expert for The Kansas City Star. An example is Figure 5.


Figure 5 - Typical Joist Seat (CASCO Detail 4/3.1 - Image Credit, Wayne Lischka

It is the opinion of the Task Force that this connection failure was a result of the secondary collapse of the wall panels falling outward from the building on the back wall. This is the only location in the building where a four stud connection was used. In other words, a failure of the roof diaphragm preceded this failure. It is not indicative of a direct uplift pull out failure, but rather the result of the catenary action of the failed roof pulling against the outwardly collapsing panels. As Figure 5 shows, many joist end seats broke free of the embed while a few of the embeds were pryed out of the panel.

4.5 ROOF DIAPHRAGM AND SUB-DIAPHRAGMS

The roof diaphragm is a critical sub-system or plane in almost all types of building construction. ACI 551 describes the typical approach used in design for these elements as a "large plate girder" analysis acting horizontally. This clearly was the case in the Joplin Home Depot.

The one unusual feature in this particular Home Depot was the inclusion of a mid-span expansion joint in the deck. This created two large three-sided buildings, which can result in large rotational forces on each of the two buildings. While this had no effect on the shear strength of the diaphragm, it does raise the possibility that the building was more flexible than a similar building designed without an expansion joint. In fact, the transverse drift of the diaphragms as designed may have exceeded the ACI 551 recommendation for lateral drift if the deck did in fact perform as a true cantilever as opposed to a typical simple span beam. This issue cannot be resolved with the information that is currently available.

Calculations we completed to confirm the basic shear strength capacity of the metal deck under code required levels of wind loads. These calculations are typically done without considering specific levels of out-of plane uplift. In all cases, the design was found to be adequate.

The Task Force examined connections between Tilt-Up walls and the steel roof system. In all cases, the connections were adequate for 1996 BOCA loads. Forces were checked at 90 MPH, Exposure C. The specified spot welds on the drawings were determined to be adequate for resisting code level uplift forces in all zones and for resisting out-of-plane forces between the roof decking and continuous steel angle wall ledgers due to out-of-plane forces on the walls. The deck was determined to be adequate for resisting simultaneous inward forces imposed by the wall panels and uplift created by 90 mph winds.

To put the wind loads in perspective, the 90 mph design results in nearly five times the base wind pressure compared to a 200 mph design since the velocity is exponential. Considering also the design differences for internal pressure and suction as well as other code prescribed parameters, the difference in design pressures is even more significant.

The Task Force performed further calculations at a 200 mph wind level per FEMA 361 storm shelter design standards to simulate the tornado wind loads and noted the following potential failure modes based on calculated forces:

- The metal deck material for all wind zones (field, edges and corner)
- The roof joists for uplift forces
- Typical joist to support connection with just two 1" x 1/8" fillet welds, and
- Typical 4" x 4" x 5/8" bearing angle and its embed connection

Note, the failure modes listed do not isolate to strictly one vulnerable piece but rather produce multiple locations and scenarios for failure.

One surprise finding was that the specified deck welded connections would not have been a failure mode in a 200 MPH wind load. For that reason, there are examples where the deck has remained intact to the joist and the joist connection certainly becomes the failure mechanism. The experience of the Task Force Chairman suggests the execution of deck fastening is one of the most common inspection deficiencies found in construction. Finally, evidence obtained in post tornado inspection of other buildings shown in Heauslers' presentation clearly documents problems with field welding of decks. The lack of special inspection records regarding this project is unfortunate. However, Home Depot informed the Task Force it was their policy to have deck welding inspections conducted by a Certified Welding Inspector before final payment was made to the contractor.

5. RESULTS AND INTERPRETATION

The narrative supplied by Mr. Oshinski was very useful since it supplied a definitive sequence of events during the structural failure. The information was supplied to Home Depot by their managers as part of a post-disaster debriefing. The sequence was as follows:

1. As the storm approached managers secured the building as per company protocol. Managers reported loud noise and vibration in the building.
2. As managers were continuing to move to interior spaces in the structure, the front entry glass windows failed suddenly and blew into the building.
3. The roof then began to fail and large sections of the interior of the roof "disappeared."
4. The building then collapsed.

This narrative is both simple and catastrophic. It appears to be a clear indication the initial structural failure was the entry structure. This allowed a sudden increase in internal pressures, which coupled with the passing vortex, lead to severe uplift forces on the structure.

The previous narrative and the photographs certainly suggest the catastrophic failure in the roof plane occurred somewhere in the central part of the structure. It is important in a failure investigation to be able to distinguish causes of primary failures from those developed as secondary in the chaos of the collapse. The onset of failure in the central part of the structure is further supported by the failure mode of the joist seat to support weld found in the 200 mph wind analysis. This problem is consistent with the Home Depot narrative.

The Task Force found no evidence of deficiencies in the design, construction or performance of the Tilt-Up concrete panels. There is no evidence that the Tilt-Up method of construction contributed to the failure. The fact the panels survived the tornado winds, only to collapse intact once the roof system failed, has led to a misconception in the public discourse. There appears to be a false expectation that the walls should have stood regardless of the condition of the roof. There is also a misconception that concrete masonry performed better because it collapsed as individual pieces. Although, under certain circumstances, there could be argument that the Tilt-Up panel performed better due to the reduction of projectiles. Regardless of whether the walls are Tilt-Up, precast, or concrete masonry they perform in the same structural fashion given the same design criteria. The masonry description by "some engineers" that it collapsed as individual units is, in fact, an indictment of non-reinforced masonry construction. This type of construction has long been discouraged by codes and engineers since it performs very poorly in even minor seismic events.

A significant issue that emerges from the article and subsequent TCA investigation is the Tilt-Up panels performed better, and had a much larger ultimate strength, than the corresponding roof diaphragm and roof connections. It seems prudent to have a roof system with a collapse factor of safety greater than the supporting Tilt-Up panels (or walls of any type). The Task Force members suggest a structural performance methodology similar to the collapse prevention resistance used for a Maximum Considered Earthquake (MCE) seismic event.

6. CONCLUSIONS AND RECOMMENDATIONS

Several clear conclusions emerge from the work of the Task Force:

1. The overall BBS failure started in the open-web, steel joist and deck roof system. The joist-to-girder welded-connection and/or the deck puddle-weld to the joist were the most vulnerable connections under severe uplift loads.
2. The Tilt-Up concrete panels performed very well and survived the extreme loads of the EF-5 event only to collapse after the roof failed.
3. Tilt-Up construction methods played no role in the failure.
4. The perception that Wal-Mart performed better since it was concrete masonry is false. The Wal-Mart took a glancing blow from the storm and the Home Depot took a direct blow.
5. The perception that the Academy Sports performed better is unclear. This former K-Mart building had smaller footprint and an 18 gauge steel roof deck, as compared to a 22 gauge steel deck on Home Depot.[3] It also likely had less severe wind load since it was further north from the storm path center.

The Task Force makes the following specific recommendations to the TCA Technical Committee and to the TCA Board of Directors:

- The TCA should work with other technical bodies to develop a procedure for more predictable collapse performance. That is, to provide roof systems (or other approaches) that has ultimate failure capacities that preclude a loss of diaphragm before a loss of individual elements. This (i.e. Luttrell) proposal is similar to the over-strength requirements for certain elements in the seismic design building codes. This procedure would be applicable to all methods of building construction and would enhance the safety of all buildings under extreme wind loads.
- Develop recommendations to be sent to the International Code Council, FEMA, and other bodies that would create a special high wind/tornado design criteria. This could also be done as a stand-alone TCA effort. This would encourage building owners to design for much higher wind resistance, at possibly a relatively reasonable cost increase. Potentially, this would provide a significant advantage for Tilt-Up construction, since it would take advantage of the inherently high wind and projectile resistance of concrete walls.
- Make specific recommendations to support points one and two to the steel Deck Institute and Steel Joist Institute to develop procedures and products to support

the previous two points. Such procedures must include design and quality control procedures for application of SDI products and SJI products in high wind applications. This could take the form of education programs, interactive web based software (see Hilti) and new design technical reports.

- Request that the SDI offer more recommendations and design guidance on the use of deck welding and other fastening systems in high uplift and diaphragm shear situations.
- Recommend to ICC and direct to building owners the use of storm shelters in lieu of designing buildings for high winds. The TCA should develop specific Tilt-Up based storm shelter designs for winds of up to 200 MPH that would compete against alternative masonry, precast, or cast-in-place designs. Storm shelter design is addressed in 2009 IBC, section 423 and ICC-500.

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APPENDIX

ITEM 1 - RESPONSE TO CLAIMS IN MADE IN AN ARTICLE PUBLISHED IN THE JUNE 25, 2011 EDITION OF THE KANSAS CITY STAR

In an effort to address incorrect claims in the original The Kansas City Star article, these claims have been summarized in the following list. A TCA response to these claims is then offered. Page references are to the original published hard-copy of the article.

Point 1, Page A1

"Home Depot used a popular tilt-up method called "tilt-up wall" that The Kansas City Star found can be deadly under certain circumstances."

Task Force: The circumstance of an EF-5 tornado can be deadly for anyone in its path as the 162 deaths have indicated. Any heavy-wall system can be deadly if not supported properly against lateral forces by a competent roof system.

Point 2, Page A1

"It is a design used in thousands of warehouses, stores and schools across the country that some engineers believe has weak links that often fail – even in winds much less ferocious than those that hit Joplin on May 22."

Task Force: It is a design that is used commonly and successfully in high wind and high seismic prone areas in which adequate building system design is required. This includes not only the wall panels but the entire structure and its connections.

Point 3, Page A1

"Indeed, some engineers interviewed by the Star said building codes for big box stores need to be strengthened, or the stores should have internal storm shelters when they're built."

Task Force: Education regarding areas of refuge, with or without storm shelters, needs to be reinforced in building protocol. Note that many people survived the catastrophic destruction by positioning themselves in these designated refuge areas.

Point 4, Page A 14

"Under high winds the roofs can be compromised and the panels in tilt-up construction can fall like dominoes said Larry Tanner, a tornado expert...from FEMA. Once you lose one wall panel, then the dominoes all start to fall so the failure becomes increasingly more catastrophic."

Task Force: This statement is inaccurate and misleading. If the roof diaphragm is removed, the panels would not have the intended restraint at the top of the panel. However, each panel would act independently and in no way act like dominoes (suggests one panel causes another to fall). If only a portion of the roof is compromised, there may still be some capacity in the structure to prevent collapse. Each scenario would have to be evaluated to determine failure modes.

Point 5, Page A14

"If the building code had required the Home Depot store to have stronger roof to wall connections it might have sustained less damage......"

Task Force: The most vulnerable connections in the Home Depot building are not the roof to wall but the attachment of the deck to joists and the joist seat connections. Recommendations to strengthen these connections and improve building performance will be made to the appropriate officials.

Point 6, Page A14

"but it is only stable when all of the connections are working", said Perry Adebar an engineer at the University of British Columbia, "It's a bit of a house of cards."

Task Force: This is the nature of all building designs and not specific to materials used. There is usually some redundancy that will prevent a collapse if certain elements fail. In the case of the tornado taking off an entire roof (deck and joist) in an instant, the redundancy is no longer present.

Point 7, Page A 14

"A few days later they said they'd use a different design: smaller precast walls made elsewhere........"

Task Force: This is a misunderstanding of the building type and the construction industry. The impression that the building would have performed any differently is false.

Point 8, Page A14

"forces were so strong that three-fourths inch diameter metal anchors for joist connections----which were embedded inside the concrete walls ----bent and literally pulled out of the hardened concrete".

Task Force: There are no details that show the anchorage as described. The failure of any embedded item in the wall would be a secondary failure due to the collapse and not a cause of the collapse.

Point 9, Page A14

"Two other big box retailers on the same corner, both of which were built of concrete blocks rather than tilt-up walls, were not as heavily damaged (per Joplin Fire Chief Mitch Randles)"

Task Force: A comparison of the buildings without a complete study in to all the differences between the buildings is irresponsible. However, the ability to maintain the roof diaphragm is the key to survival of the walls, whether block or concrete.

Point 10, Page A14

"Tanner said tilt-up wall panels were usually not connected to one another meaning they tend to fall progressively."

Task Force: The walls are not connected which means that one cannot cause the next to fall, opposite of the statement made by Tanner.

Point 11, Page A15

Tanner and other engineers said that concrete roofs----which some Home Depot stores in hurricane country have----"would add weight to the roof system and could prevent roof failures."

Task Force: The additional weight can help to counteract the uplift forces which can improve the ability for the roof diaphragm to perform. However, this would be based on code-enforced loads only and is not standard practice without other functions (such as acoustics). Also, this approach is much more costly than improving the deck strength, connections, and steel joist uplift strength.

Point 12, Page A15

The final section of the report is a narrative discussing the need for more stringent codes.

Task Force: Although there are specific items that the Task Force would deem appropriate for review by the code council, making the base codes more stringent would not improve the performance significantly for tornado forces. The FEMA 361 code is available for specification when the building classification requires a shelter.