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The Design of Safe Spaces in Healthcare Facilities Vulnerable to Tornado Impact in Central US

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Abstract**—**In the wake of recent disasters happening around the world such as earthquake in Italy (January, 2017); hurricanes in the United States (US) (September 2016 and September 2017); and compounding disasters in Haiti (September 2010 and September 2016); to our best knowledge, never has the world seen the need to work on preemptive rather than reactionary measures to salvage this situation than now. Tornadoes are natural hazards that mostly affect mid-western and central states in the US. Tornadoes, like all natural hazards such as hurricanes, earthquakes, floods and others, are very destructive and result in massive destruction to homes, cause billions of dollars in damage and claims many lives. Healthcare facilities in general are vulnerable to disasters, and therefore, the safety of patients, health workers and those who come in to seek shelter should be a priority. The focus of this study is to assess disaster management measures instituted by healthcare facilities. Thus, the sole aim of the study is to examine the vulnerabilities and the design of safe spaces in healthcare facilities in Central US. Objectives that guide the study are to primarily identify the impacts of tornadoes in hospitals and to assess the structural design or specifications of safe spaces. St. John's Regional Medical Center, now Mercy Hospital in Joplin, is used as a case study. Preliminary results show that the lateral base shear of the proposed design to be 684.24 ton (1508.49kip) for the safe space. Findings from this work will be used to make recommendations about the design of safe spaces for health care facilities in Central US.

Keywords**—**Disaster management, safe spaces, structural design, tornado, vulnerability.

I. Introduction

TORNADOES are natural hazards that mostly affect mid-western and central states in the United States (US) – Iowa, Oklahoma, Nebraska, Missouri, Minnesota and Kansas [1], [2]. Tornadoes, like all natural hazards such as hurricanes, earthquakes, floods and others, are very devastating and result in massive destruction to homes, property and infrastructure, and cause fatalities (mostly from flying debris) [1], [3].

Healthcare facilities in general are vulnerable to disasters. The safety of patients, health workers as well as those who come in to seek shelter should be a priority [4], [5]. A study by Gray et al. [6] indicates that in the event of a disaster, hospitals or healthcare facilities are supposed to continue functioning [4]. In addition, several studies [7]-[9] suggest that a disaster response plan is a requisite for every hospital in the US, as required by the Joint Commission for Accreditation of Healthcare Organization (JCAHO). Furthermore, the structural (load-bearing system) and non-structural (architectural elements and installations) of hospitals/healthcare buildings are also vulnerable in the event of tornadoes [4], [5], [8]. Location, type of disasters, design materials and construction, shape of building as well as orientation are the key vulnerability indicators of a building during disasters [5], [8].

A case study on Birmingham Nursing and Rehabilitation Center, La Rocca, Greenbiriar, revealed that in the event of the Tuscaloosa Tornado, these health facilities did not have safe spaces or safe rooms. A Safe room is defined by the Federal Emergency Management Agency (FEMA) as "an interior room, or hallway, a space within a building or an entirely separate building designed and constructed to provide near-absolute life-safety protection for its occupants from tornadoes or hurricanes" [10]-[12]. The study therefore seeks to assess the disaster management measures put in place by hospitals or health care facilities in the US.

During the Enhanced Fujita-scale (EF-5) 2011 Joplin Tornado that struck Missouri as well as smaller communities and rural areas between the two cities, homes, infrastructure, and public facilities were wrecked and devastated. Many lives were claimed and the resulting damage was in the billions of dollars. The storm destroyed many vital institutions; and St John's Mercy Regional Medical Center Hospital, now Mercy Hospital, was not left out. In the event, 14 patients lost their lives [13]. Consequently, the building was demolished and reconstructed. Mercy Hospital now boasts of being a tornado-proof hospital with safe zones and reinforced walls and ceilings that can resist an EF-5 Tornado [14]. Furthermore, hospitals are supposed to function at the event of a disaster or an emergency [4], but during Hurricane Irma in September 2017, eight patients died in a nursing home in Florida. This has however raised concerns of the safety of health care facilities with respect to disasters [15].

The question that comes to mind following the foregoing is "Do hospitals in Central US have safe zones during disasters?" It is therefore important to look into ways by which research can help to assess the vulnerability of safe spaces within hospitals in the Central US.

II. Central US and Tornado Risk Maps

The study location is Central US. Fig. 1 shows the map of the US highlighting the states that constitute Central US, which comprises of West North Central, East North Central, West south Central and East South Central.

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Fig. 1 Map of US showing Central US states

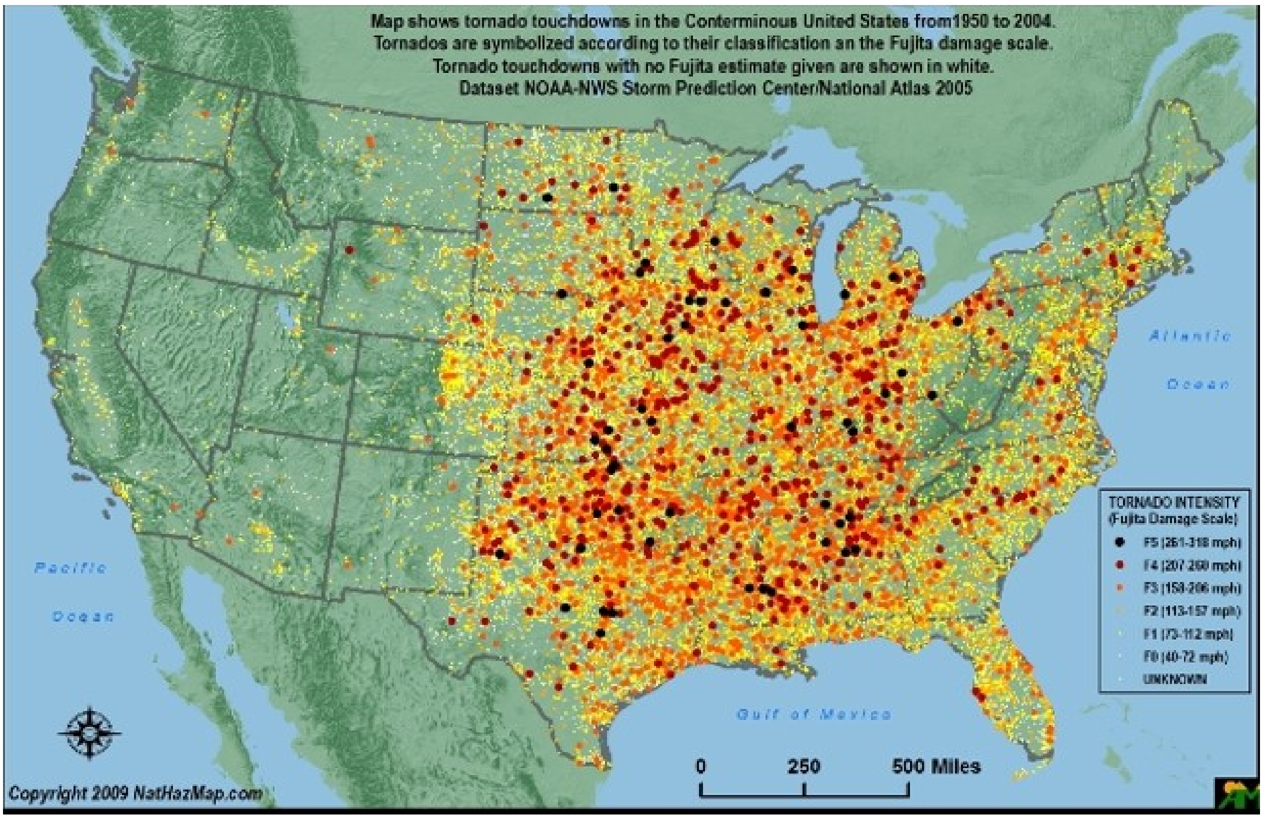

Fig. 2 Tornado activities in the US (1950-2014) [16]

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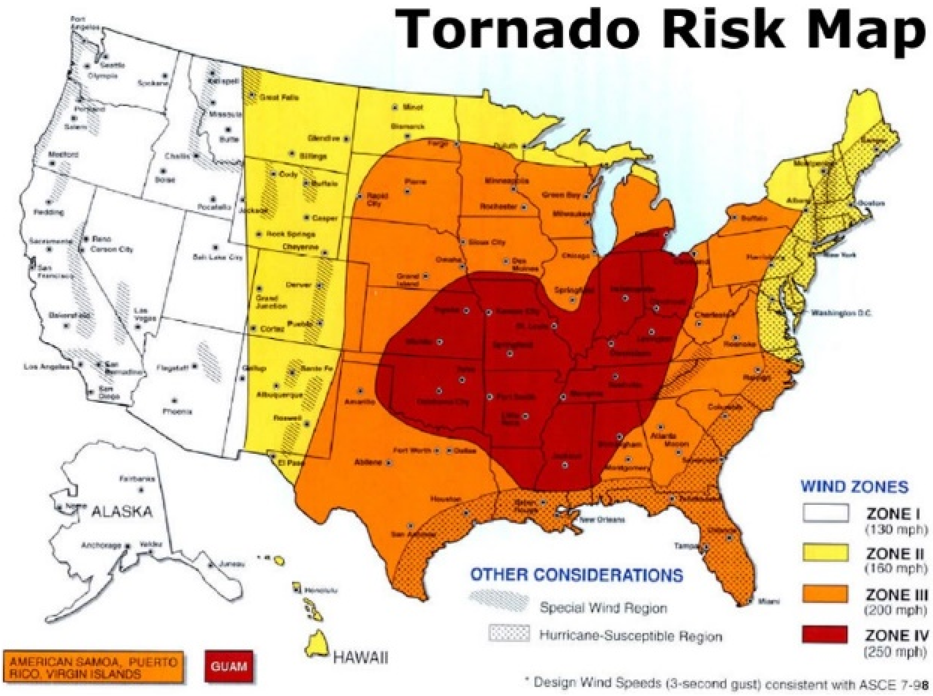

Fig. 3 Tornado Risk Map [17]

EF Rating	Wind Speeds	Expected Damage	
EF-0	65-85 mph	'Minor' damage: shingles blown off or parts of a roof peeled off, damage to gutters/siding, branches broken off trees, shallow rooted trees toppled.	
EF-1	86-110 mph	'Moderate' damage: more significant roof damage, windows broken, exterior doors damaged or lost, mobile homes overturned or badly damaged.	
EF-2	111-135 mph	'Considerable' damage: roofs torn off well constructed homes, homes shifted off their foundation, mobile homes completely destroyed, large trees snapped or uprooted, cars can be tossed.	
EF-3	136-165 mph	'Severe' damage: entire stories of well constructed homes destroyed, significant damage done to large buildings, homes with weak foundations can be blown away, trees begin to lose their bark.	
EF-4	166-200 mph	'Extreme' damage: Well constructed homes are leveled, cars are thrown significant distances, top story exterior walls of masonry buildings would likely collapse.	
EF-5	> 200 mph	'Massive/incredible' damage: Well constructed homes are swept away, steel-reinforced concrete structures are critically damaged, high-rise buildings sustain severe structural damage, trees are usually completely debarked, stripped of branches and snapped.	

Fig. 4 Tornado scale showing EF rating and expected damage [19]

Tornado activities in the US from 1950 (Fig. 2) and a Tornado risk map (Fig. 3) were looked at side-by-side. From the maps, Kansas, Alabama, Mississippi, Tennessee, Arkansas, Oklahoma, Missouri, Kentucky, Ohio and Indiana are in the high-risk areas and the healthcare facilities or hospitals in these areas will be of high importance.

III. Impact of Tornadoes on Hospitals

The effects of Tornadoes on the built environment as against wind scale was also examined and Fig. 4 shows the tornado scale with expected damages. According to [18], from 1950-2011, 68% of all tornado facilities were caused by tornadoes EF3 and greater. Due to the study by [18], EF-3 to EF-5 were used to identify the impacts of tornadoes in hospitals in the Central US.

TABLE I
IMPACT OF TORNADOES IN OKLAHOMA [MODIFIED FROM 20]

Scale	Date	Number of tornadoes	Total fatalities	Total injuries	Cost of structural damage (s)
EF 3	1950-2015	193	256	1206	800-1 billion
EF 4	1950-2013	56	130	5285	1-2 billion
EF 5	1955-2013	8	256	2286	100-200 million

TABLE II
IMPACT OF TORNADOES IN MISSOURI [MODIFIED FROM 20]

Scale	Date	Number of tornadoes	Total fatalities	Total injuries	Cost of structural damage(s)
EF 3	1950-2015	106	74	1206	400-600 million
EF 4	1952-2011	39	130	2006	300-500 million
EF 5	1957-2011	2	360	2507	30-50 million

Regarding the impact of tornadoes on the high risk areas, assessment was based on the cost of structural damage, number of tornadoes and total fatalities and total injuries as against the tornado scales of EF-3 to EF-5. Tables I and II illustrate the impact of tornadoes in Missouri and Oklahoma [20].

Fig. 5 shows the impact of Tornado (Moore Tornado (EF-5) in 2013) on the structural system of Moore Medical Center, while Fig. 6 illustrates the impact of Joplin Tornado (EF-5) on St John's Regional Medical Center (SJRMC).

Fig. 5 Impact of the Moore Tornado on Moore Medical Center [21]

Fig. 6 Impact of Joplin Tornado on SJRMC [14]

IV. DESIGN AND CONSTRUCTION OF SAFE SPACES

In order to assess the vulnerabilities and specifications or requirements of safe spaces in hospitals, the Hospital Incident Command System (HICS) was studied. During emergencies, hospitals either transfer patients to a bigger hospital, evacuate the building after several training and exercises on how to evacuate the facility, put shelter in place for the community or use triage to sort patients for treatment [8], [11].

A. Vulnerabilities

Hospitals are vulnerable to disasters. Patients and health workers are also vulnerable. Vulnerable populations are populations who are not able to "evacuate from the area of an impending storm" [10]. The most vulnerable populations during disasters in hospitals are children, elderly with chronic diseases, bedridden patients and pregnant women [4], [22]. The hospital building itself is also vulnerable. The structures – load-bearing system and non-structural building system – can be adversely affected [8].

B. Safe Spaces

As earlier mentioned, a safe space is a space within a building "designed and constructed to provide near-absolute or absolute life-safety protection for its occupants from tornadoes and hurricanes" [10]. The design consideration for a safe room includes maximum occupancy time of 2 hours, 0.465 square-meters per person (m^2/p)) (5ft^2/p), 0.9 m^2/p (10 ft^2/p) wheel chair, 2.79 m^2/p (30 ft^2/p) Fig. 5, emergency provisions such as water, communications equipment and supplies. Safe rooms can also be multi-use safe rooms such as cafeterias, hallways bathrooms, surgical rooms [10]-[12]. The cost of a safe room is also dependent on the location, design, whether it is new or a retrofit, and the design wind speed [10].

C. Structural Design of Safe Spaces

Structural design of safe rooms is based on International Code Council (ICC) 500 and American Society of Civil Engineers (ASCE) 7-10 standards. The design parameters, however, are based on:

1. Single-use versus multi-use,
2. Design complexity,
3. Safe room design wind speed,
4. Safe room debris impact resistance design criteria,
5. Foundation,
6. Resistance to large wind-borne debris loads, and
7. Resistance to seismic loads [12].

This study will employ the Safe Room Design Wind Speed Parameter.

Some construction materials that are mostly used for safe rooms, are, Concrete Masonry Unit (CMU), precast concrete, Reinforced concrete, Reinforced Masonry, Insulated concrete forms etc. [12].

For the structural design, however, connections, floors, roof system, foundations, doors and windows should be looked at.

1. **Connections:** Connections prove vital during tornado hazards, this is because they help transfer loads, and hence, should be strong enough to prevent deformation. A deficiency in the connections will lead to structural damage of the safe room and loss of life. Connections used are screws, steel bolts, welds, steel stuffs. Size and number depend on the wind pressure acting on it.
2. **Slabs (floor):** Slabs must be 88.9 mm (3.5 inches) thick and have steel reinforcement of a #4 minimum and a minimum spacing of (457.2 mm) 18 inches.
3. **Foundations:** Reinforcement bars must go all the way from the walls to the foundation [12]. Fig. 7 shows a typical design of a safe space.

FEMA recommends that the design wind speed for a safe space should be 402 kph (250 mph) regardless of location. The importance of safe spaces should not be ignored. The main purpose is to protect from death or injury. Internal safe spaces should be designed to receive design wind pressures and potential wind-borne debris impacts that are applicable to stand-alone ones. In effect, it should be assumed that the surrounding structure will not provide any shield or protection to the safe room [12].

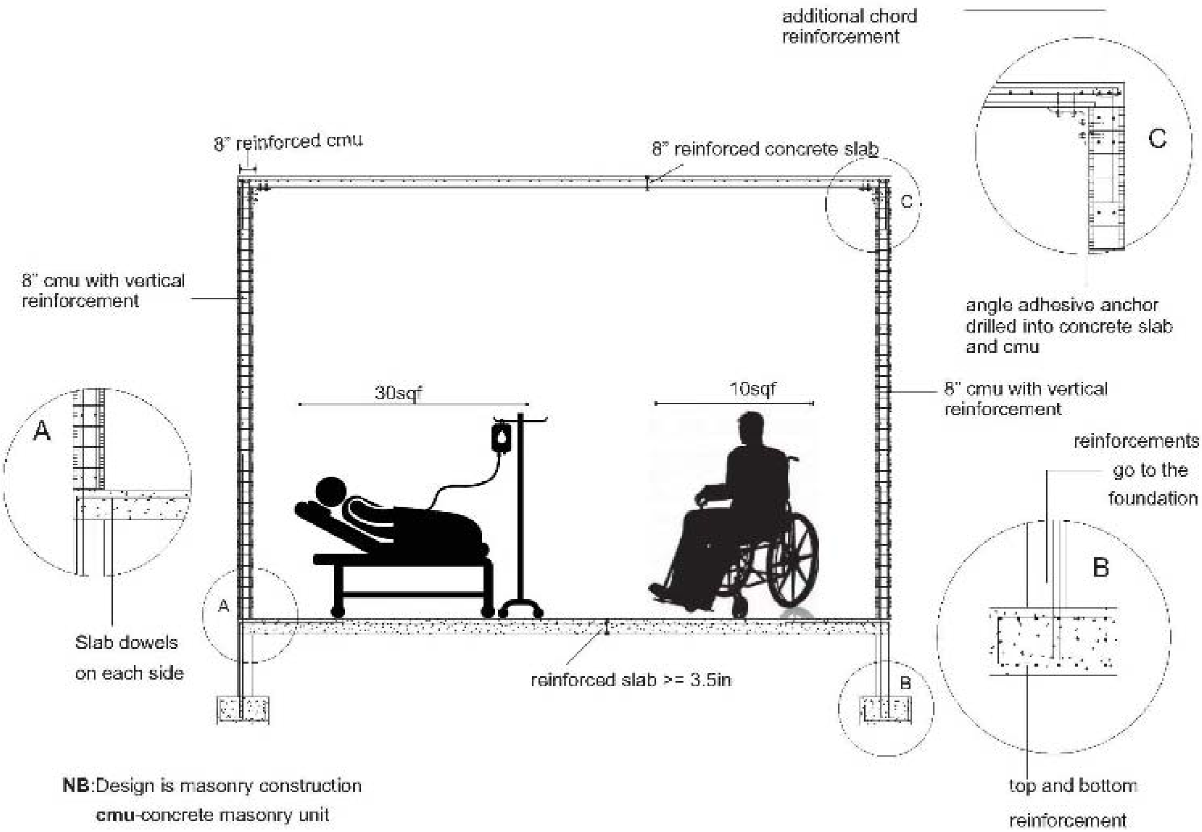

Fig. 7 Typical structural safe space design [Modified from 23]

V. Case Study of St John's Regional Medical Center (SJRMC)

A. Events

An EF-5 tornado destroyed St John's Regional Medical Center in Joplin in May 2011. The storm blew out all the windows of the building, and portions of the roof were pulled off and the infrstructure was severely damaged. Generators were destroyed and so were communications equipment [24], [25]. During the storm, 183 patients were in the hospital. There were patients in critical care, emergency rooms, labor rooms as well as surgical rooms. Three collection points were used for evacuation namely, the East Side, West Side and Conference Center (Fig. 8). The methods of evacuation employed included ambulatory and wheel chairs, mattresses, doors, medical sleds and triage. Critical patients were transferred to other hospitals. Incident command systems were used [25].

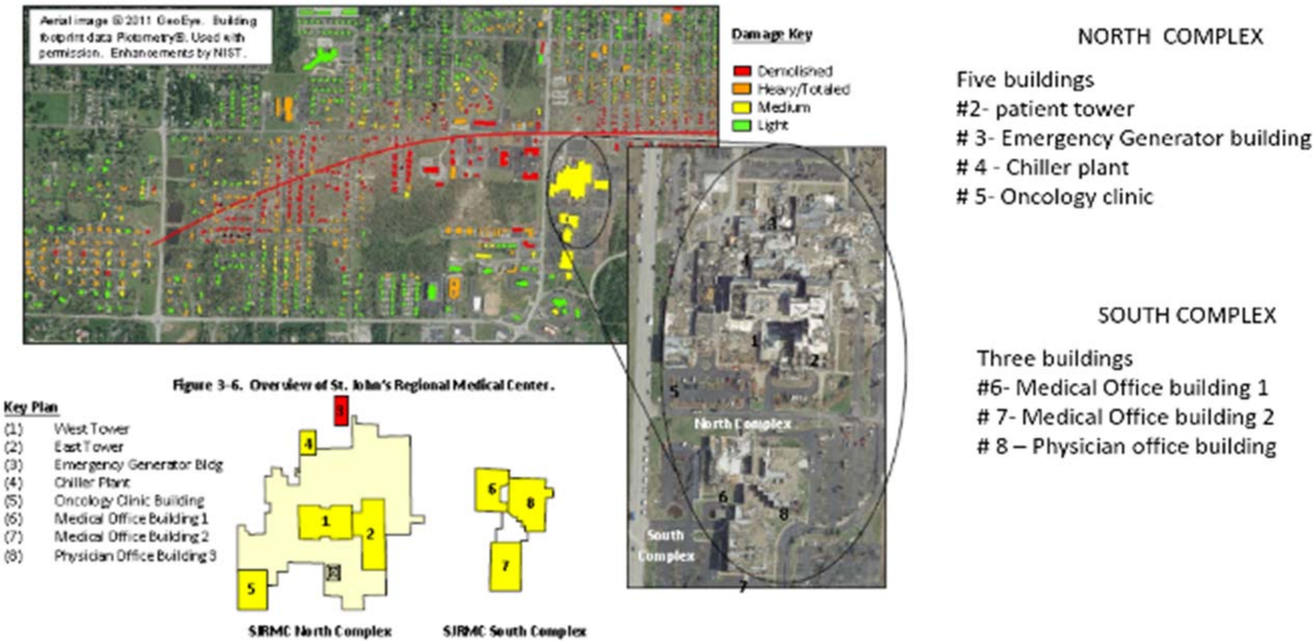

Fig. 8 Layout of SJRMC [13]

TABLE III
DESIGN INFORMATION FOR WEST TOWER [MODIFIED FROM 13]

BUILDING CODE	DESIGN WIND SPEED	MWFRS	FLOOR SYSTEM	C&C
1960 BOCA BBC	70 mph or 85 mph in 3 second gusts	Cast in place reinforced concrete with a mean roof height of 86.7 ft.	Reinforced concrete (RC) waffle slab floor.	Single story curtain wall panels made from aluminum framing and resistant glass window on 5th floor

TABLE IV
DESIGN INFORMATION FOR EAST TOWER [MODIFIED FROM 13]

BUILDING CODE	DESIGN WIND SPEED	MWFRS	FLOOR SYSTEM	C&C
1984 BOCA B/NBC	70 mph or 85 mph in 3 second gusts	Nine story with moment connections and steel cross bracing.	Composite concrete-steel deck floor	Single story curtain wall panels made from aluminum framing and dual pane insulated glass glazing and precast concrete column

B. Tornado Impacts on the Building Structural System

Hospitals are categorized as Risk Category IV: “as essential facilities in the above references and defined as “buildings and other structures that are intended to remain operational in the event of extreme environmental loading from flood, wind, snow, or earthquakes” [26].

Building codes are important for structural design. Prior to the 2011 Joplin Tornado, the City of Joplin adopted a building code through Ordinance No. 2008–068

- 2006 ICC International Building Code (IBC),
- 2006 ICC International Residential Code for One– and Two–Family Dwellings (IRC) [13].

The West Tower and East Tower (Fig. 8) was studied since it housed the most vulnerable populations. The study was a structural analysis based on Building codes, Design wind speeds, Main Wind Force Resisting System (MWFRS), Floor system and Components and Cladding (C&C).

Table III illustrates the design information of the West Tower. There was no structural damage that is, damage to the Lateral load system and Gravity load system (MWFRS). However, the building’s Components and Cladding system (C&C), which consist of vertical glass windows were damaged. Additionally, unreinforced Concrete Masonry Units (CMU) collapsed. Interior partitions and HVAC equipment were damaged as well [13].

Table IV illustrates the design information of the East Tower. There was no structural damage that is, damage to the Lateral load system and Gravity load system (MWFRS). However, the building’s Components and Cladding system (C&C) which consist of glass curtain wall was damaged Additionally, Interior partitions and HVAC equipment were also damaged [13]. It should however be noted that the basic wind speed that affected the East and West Tower was 274 kph (170 mph) +/- 32 kph (20 mph). Based on today’s standards, it will be categorized as 120 mph and the building would have been severely damaged.

C. New Building Construction After the Tornado Impact

After the storm, the hospital further put up a new building structure which can withstand up to EF-5 tornado and serves as a safe haven should a tornado strike (Fig. 9). The construction materials for the new design consist of a concrete (precast concrete) shell for the building, high-impact laminated glass that can withstand windspeeds of up to 402 kph (250 mph) for critical areas, barrier storm doors and fortified safe zones with reinforced concrete walls and ceilings on each floor. The design also includes a 137 m (450 ft) underground tunnel for a central utility plant which will keep the hospital running after a natural hazard hits [24], [25].

Fig. 9 New Hospital after the Tornado [25]

VI. Wind Design Specification (ASCE-7-10)

The American Society of Civil Engineers (ASCE 7-10) building code is used for most wind load calculations. Table V shows the steps for wind load calculations in ASCE 7-10 (Chapter 27). Fig. 13 shows the wind speed map used for basic wind speed according to FEMA.

The basic calculations for the wind loads are Velocity Pressure (q_z), Fig. 10, Pressure on MWFRS for buildings (p) Fig. 11, and Pressure on C&C and Attachments (p) Fig. 12. The ICC however recommends exposure category C to be used for safe spaces.

$$q_z = 0.00256\, K_z\, K_{zt}\, K_d\, V^2$$

where:

q_z = velocity pressure (psf) calculated at height z above ground
K_z = velocity pressure exposure coefficient at height z above ground
K_{zt} = topographic factor
K_d = directionality factor = 1.0
V = safe room design wind speed (mph) (from Figure B3-1 or B3-2)

Fig. 10 Velocity Pressure Equation [12]

$$p = qGC_p - q_i\,(GC_{pi})$$

where:

p = pressure (psf)
q = q_z for windward wall calculated at height z above ground
q = q_h for roof surfaces and all other walls
G = gust effect
C_p = external pressure coefficients
q_i = q_h = velocity pressure calculated at mean roof height
GC_{pi} = internal pressure coefficients

Fig. 11 Pressure on MWFRS for buildings [12]

$$p = q_h\,[(GC_p) - (GC_{pi})]$$

where:

p = pressure (psf)
q_h = velocity pressure calculated at mean roof height
GC_p = external pressure coefficients
GC_{pi} = internal pressure coefficients

Fig. 12 Pressure on C&C and Attachments [12]

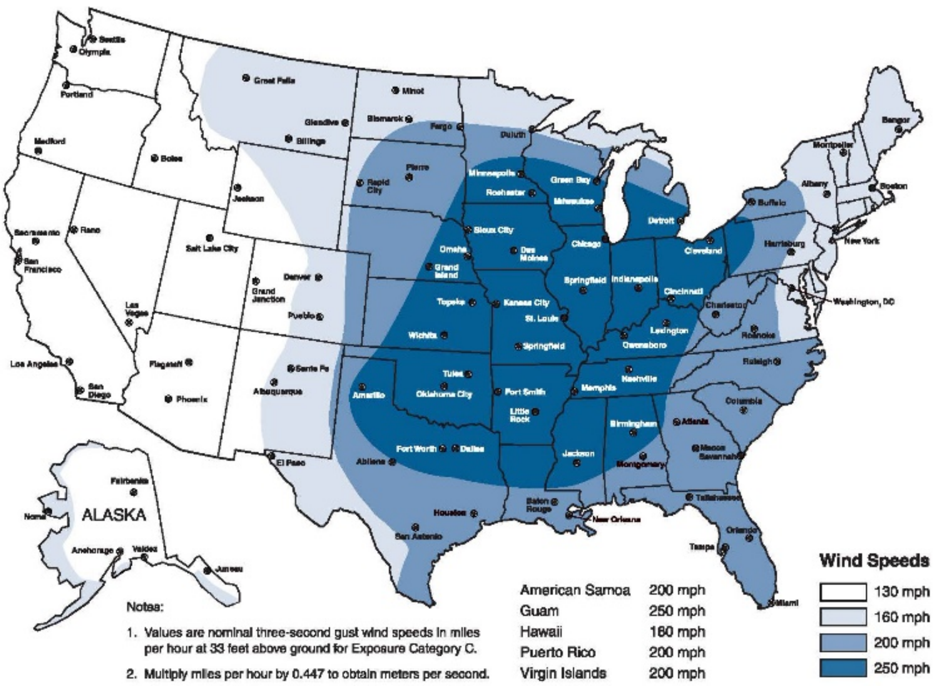

Fig. 13 Wind Speed Map [12]

TABLE V
STEPS FOR WIND LOAD CALCULATIONS [26]

Table 27.2-1 Steps to Determine MWFRS Wind Loads for Enclosed, Partially Enclosed and Open Buildings of All Heights	
Step 1:	Determine risk category of building or other structure, see Table 1.4-1
Step 2:	Determine the basic wind speed, *V*, for the applicable risk category, see Fig. 26.5-1A, B or C
Step 3:	Determine wind load parameters: ➢ Wind directionality factor, *Kd*, see Section 26.6 and Table 26.6-1 ➢ Exposure category, see Section 26.7 ➢ Topographic factor, *Kzt*, see Section 26.8 and Table 26.8-1 ➢ Gust Effect Factor, *G*, see Section 26.9 ➢ Enclosure classification, see Section 26.10 ➢ Internal pressure coefficient, (*GCpi*), see Section 26.11 and Table 26.11-1
Step 4:	Determine velocity pressure exposure coefficient, *Kz* or *Kh*, see Table 27.3-1
Step 5:	Determine velocity pressure *qz* or *qh* Eq. 27.3-1
Step 6:	Determine external pressure coefficient, *Cp* or *CN* ➢ Fig. 27.4-1 for walls and flat, gable, hip, monoslope or mansard roofs ➢ Fig. 27.4-2 for domed roofs ➢ Fig. 27.4-3 for arched roofs ➢ Fig. 27.4-4 for monoslope roof, open building ➢ Fig. 27.4-5 for pitched roof, open building ➢ Fig. 27.4-6 for troughed roof, open building ➢ Fig. 27.4-7 for along-ridge/valley wind load case for
Step 7:	Calculate wind pressure, *p*, on each building surface ➢ Eq. 27.4-1 for rigid buildings ➢ Eq. 27.4-2 for flexible buildings ➢ Eq. 27.4-3 for open buildings

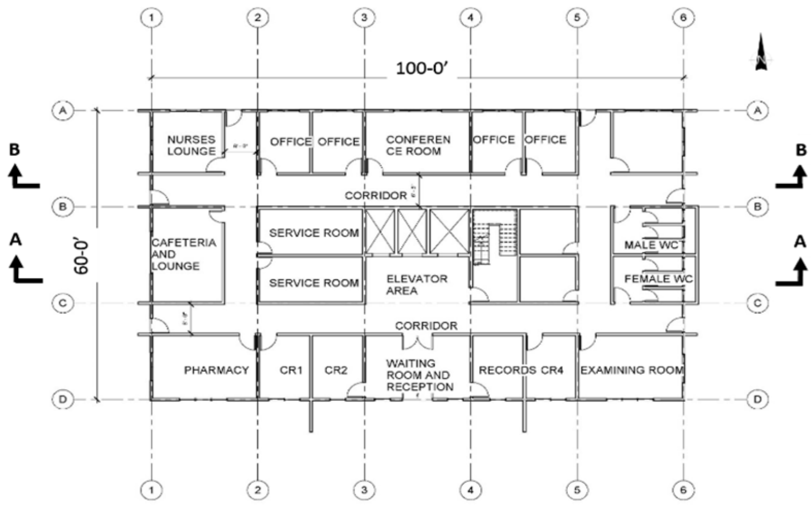

Fig. 14 Typical Floor plan [27]

VII. METHODOLOGY

The methodology for this research involves a precedent study of Mercy Joplin Hospital, reviewing the structural design and building codes employed. Additionally, the structural system for a hospital will be designed, including the calculation of gravity loads and lateral loads. The design will then be analyzed with RAM software (Structural Engineering Software).

A. Design

1. Description

The design is a 18.2 m × 30.5 m (60 ft × 100 ft) hospital with total height of 13.7 m (25 ft). Floor to floor dimension is 3.1 m (10 ft). Table VI illustrates this.

The building will be located in Joplin, Missouri. Therefore, all loads such as seismic, snow and wind loads will employ the City of Joplin's Standards.

TABLE VI
DIMENSIONS FOR HOSPITAL DESIGN [27]

SPECIFICATIONS	MAGNITUDE
Height of building	13.7 m (45 ft)
Number of floors	4 floors
Height from floor to floor	3.1 m (10 ft)
Length of building	30.5 m (100 ft)
Breadth of building	18.2 m (60 ft)

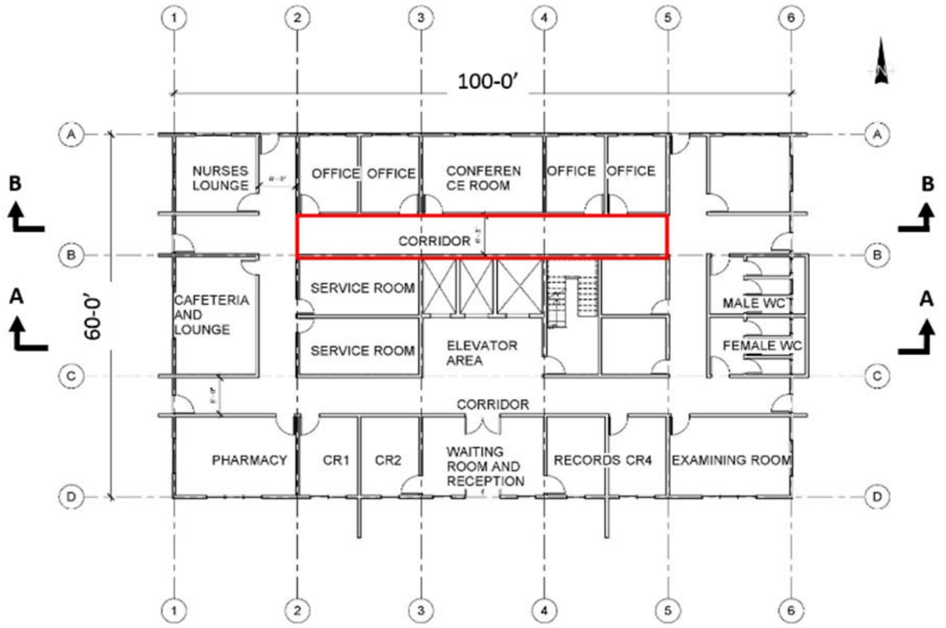

Fig. 15 Plan showing safe space [27]

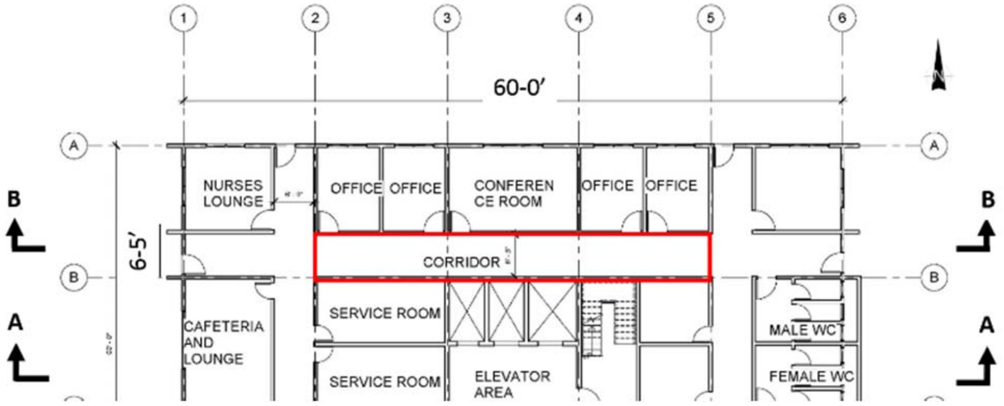

Fig. 16 Plan of the Safe Space [27]

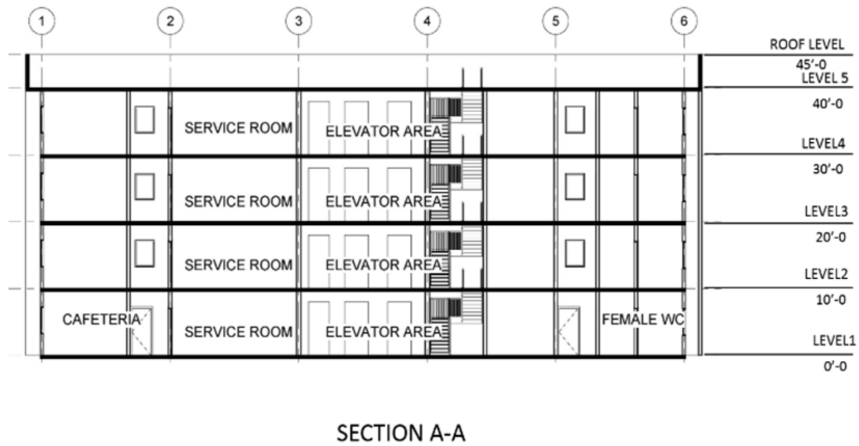

Fig. 17 Section through the Whole Building [27]

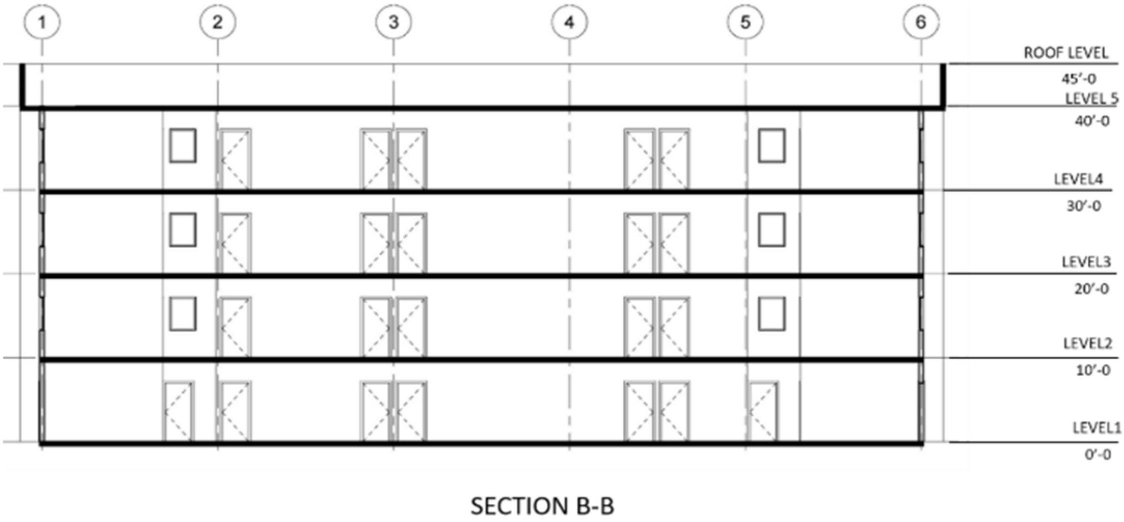

Fig. 18 Section through the Safe Space [27]

The safe space employed for the design is a corridor, which doubles up as a safe space (Figs. 15 and 16). The dimensions are 2 m × 30.5 m (6.5 ft × 60 ft).

Applicable codes used for the design include:

1. American Society of Civil Engineers (ASCE) 7-10,
2. American Concrete Institute (ACI) 318-11, and
3. International Building Code (IBC) 2012.

1. Gravity Loads

a. Dead Loads

For dead loads, Table C-31 in ASCE 7-10 was used for calculations based on design components. Table VII shows the estimated dead load calculations.

TABLE VII
ESTIMATED DEAD LOAD CALCULATIONS [27]

COMPONENTS	LOAD
Self-weight	As calculated
Exterior Cladding	0.9 Kpa (20 psf)
Roof load	1.2 Kpa (25 psf)
Mechanical Equipment	0.48 Kpa (10 psf)
TOTAL	

b. Live Loads

For live loads, Chapter 4, Table 4.1 in ASCE 7-10 was used for calculations based on building occupancy. Table VIII shows the estimated live load calculations. Roof live load was 0.96 Kpa (20 psf) and 5.7 Kpa (120 psf) as used for the whole building.

TABLE VIII
ESTIMATED LIVE LOAD CALCULATIONS [27]

COMPONENTS	LOAD
Corridor and Entire building	5.7 Kpa (120 psf)
Roof	0.96 Kpa (20 psf)

c. Snow Loads

ASCE 7-10 (Chapter 7) was used for snow load calculations (P_f). The building employed a flat roof for the design since the roof will house the hospital's mechanical equipment. The ground snow load, P_g, for Joplin, Missouri is 0.91 Kpa (19 psf). The total snow load for the hospital is 0.92 Kpa (19.31 psf), which was even, less than live load. Hence, snow load would not be the controlling load case for gravity loads analysis, as roof live load is greater.

1. Lateral Loads

a. Seismic loads

For seismic provisions, the risk category is Category IV, since it is a hospital. The US Geological Survey (USGS) site [28] was used for calculations for Spectral accelerations at 1-second periods (SD_1) and Spectral accelerations at 1 short periods (SD_S). From the calculations, the hospital is in Seismic Design Category A and buildings assigned to Seismic Design Category A need only comply with the requirements of Section I.D. Non-structural components are exempt from seismic design requirements. This implies that seismic loads would not be the controlling load case for lateral loads analysis, since the building is located in Seismic Design Category A.

b. Wind Loads

In order to determine lateral loads by which the structure is exposed to, Chapter 26, Chapter 27, and Chapter 30 of ASCE 7-10 were used. After a thorough review of these chapters, the wind input parameters were determined and displayed in Tables IX and X.

TABLE IX
WIND LOAD INPUT PARAMETERS FOR THE WHOLE BUILDING [27]

Risk Category	IV
Basic Wind speed, V	193 kph (120 mph)
Wind Directionality Factor, Kd	1.00
Exposure Category	C
Topographic Factor, Kzt	1.00
Gust Factor, G	0.85
Enclosure Classification	Enclosed
Internal Pressure Coefficient, Gcpi	+/- 0.18

TABLE X
WIND LOAD INPUT PARAMETERS FOR SAFE SPACE [27]

Risk Category	IV
Basic Wind speed, V	402 kph (250 mph)
Wind Directionality Factor, Kd	1.00
Exposure Category	C
Topographic Factor, Kzt	1.00
Gust Factor, G	0.85
Enclosure Classification	Enclosed
Internal Pressure Coefficient, Gcpi	+/- 0.55

These inputs are used to calculate pressure and base shear values to be applied to the Main Wind Force Resisting System (MWFRS) for the entire structure. The same input parameters are used to find components and cladding wind pressures. Due to the addition of a FEMA rated safe room within the building, separate wind load calculations were completed for this space. For the safe room, the basic wind speed was increased to 402 kph (250 mph) and per FEMA recommended best practices; the internal pressure coefficient is taken as 0.55.

VIIII. PRELIMINARY RESULTS

The base shear values have been calculated for both the main building and the safe space (Fig. 19) to be applied to the Main Wind Force Resisting System (MWFRS). The base shear value for the safe space is 684.24 ton (1508.49kip). The design will further be analyzed with RAM software to get further results for the design.

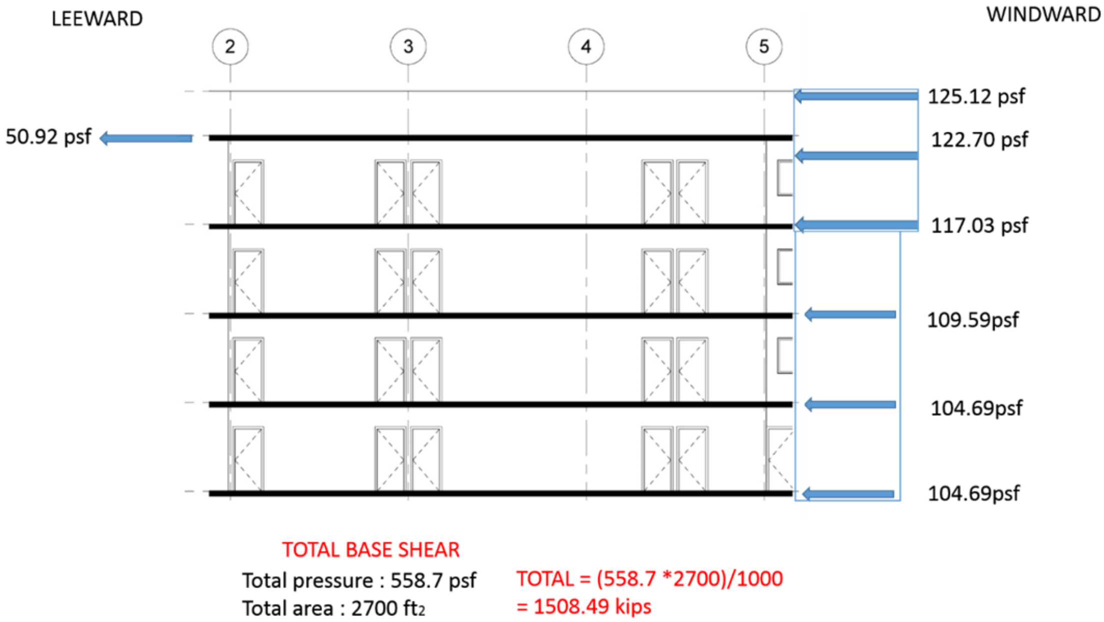

Fig. 19 Total base shear of the whole building [27]

IX CONCLUSION

The next step involves structural analysis of the design using RAM structural Analysis Software.

The results will be used as a recommendation for hospitals in tornado-prone areas (high-risk areas mentioned) to incorporate safe rooms design according to FEMA standards or retrofit existing buildings to reduce the vulnerability of patients, hospital workers and hospital structural system to the impact of tornadoes. The next step involves structural analysis to check the design.

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