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Original article

Understanding the Performance of Historic Masonry Structures in Mayfield, KY after the 2021 Tornadoes

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ABSTRACT

Due to the rise in tornadoes in the United States, the built environment continues to suffer damage. Masonry buildings comprise a significant portion of the built heritage environment for most countries and are susceptible to natural hazards. However, research at the intersection of extreme wind loading and structural strengthening often neglects historic and aging infrastructure, particularly unreinforced masonry buildings, leading to their exclusion from the building code. This study aims to identify various factors that affect damages to unreinforced masonry structures during tornado loading. To begin, the structural performance of historic masonry constructions after the Mayfield, KY tornado in 2021 was evaluated, with multimodal data collected on-site, including aerial photographs, street-view imagery, and detailed field notes on observed damages. The on-site data included aerial photographs, street-view imagery, and detailed field notes for the observed damages. This data was supplemented by archival research and analyzed to identify the underlying relationships between building attributes and damage levels. The results indicate that damages in historic buildings were extensive and proportional to the year of construction and the distance from the tornado but not necessarily to the retrofit status.

1. Introduction

According to the National Oceanic and Atmospheric Administration (NOAA), on average, almost one thousand tornadoes occur in the United States every year [3]. These disasters can cause extensive damage [26], despite their low probability of occurrence, and barely allow 10-15 minutes of warning time [50]. The tornado's intensity is estimated based on the damage observed following the event and ranges from EF0 to EF5 (Enhanced Fujita Scale) [31]. Even with yearly tornadoes impacting the built environment in the United States [32], only recently have tornado loads been added to the design loads standard ASCE7-22 [5].

Post-tornado reports have identified common damage failure patterns recurrently observed in impacted buildings, however, these have primarily focused on wooden and residential constructions [42,47]. The pressures acting on the structure's surface are spatially heterogeneous and dependent on several factors, such as the configuration of the structure, wind speed and direction, and the surrounding environment [53]. The other factors complicating the impact of tornadoes on low-rise structures are the increased turbulent intensities felt at lower heights and the variations in roof loading as a result of the changing geometry [13]. This leads to structural damages and component-level failures, such as wall and roof collapses [16], often preceded by connection failures due to internal pressurization or inappropriate load paths [23].

According to the risk categories described in the design standards, historic buildings fall under risk category II. With the current standard focusing on tornado design loads for risk category III or IV structures [5], historic buildings remain excluded making them unprepared for extreme wind loading conditions. It is also pertinent to mention that the wind speeds in the current design standards are estimated from tornado probability maps, for lower intensity tornadoes. A considerable portion of the downtowns in the United States has high concentrations of 'aging historical buildings' [9], built between the mid-1800s and 1900s primarily as one-two storey low rise structures [43]. These low-rise structures are more susceptible to wind damage [16] resulting from higher turbulence at lower heights and the extreme fluctuation in the roof loads [13]. The damages during extreme wind conditions usually vary as a function of the roof pitch [45], the garage's presence [3], roof-to-wall connections [30] and the distance from the tornado [4].

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Historic buildings' behavior has primarily been studied for seismic disasters, while wind-induced damages are relatively unexplored. While multiple authors have evaluated wind loading and building behavior for low-rise buildings, few studies focus on masonry constructions. During an investigation by Sparks et al. [51], where the performance of low-rise masonry structures to extreme wind loads was studied, the results showcased the extensive damages seen for these structures. In an attempt to better understand the direct implications of extreme wind damage on the historic built environment, this paper investigates the impacted historic buildings in Mayfield following the December 2021 tornado. Considering the multimodal data collected post-disaster, this work aims to elucidate any relationships between historic building features and the resulting damages.

1.1. The 10th December, 2021, Midwest Tornado Outbreak

The higher-than-average temperatures of December 2021 [35] combined with the La Nina conditions [21] resulted in an off-season tornado outbreak in the southeast states of the United States. This supercell thunderstorm led to the formation of almost 30 tornadoes in the region [6]. One of the most devastating tornadoes generated in this outbreak was the Midwest tornado, which rotated at 94 mph for four hours [48], covering almost 250 miles [35]. This tornado tore through Arkansas, Missouri, Tennessee, and Kentucky leaving a trail of extensive damage, with Kentucky (KY) being the worst hit state [49]. Some of the main impacted towns in KY included Mayfield, Cambridge Shores, Princeton, and Dawson Springs, and this event was one of the most destructive tornadoes to hit the state since 1890 [12].

The tornado caused disruption of utilities such as drinking water, natural gas, and electricity [10], and the damage to the built environment was extensive. The Governor of Kentucky suggested that it would take years to recover from the disaster's impact on society [57]. According to Erdman [8], a night-time tornado can almost double the mortality rate due to higher occupancy of the built environment, which may have resulted in a high mortality rate in Kentucky. The initial loss estimates suggest that the event was the costliest tornado in the United States, with almost 18 billion dollars in loss [10]. This loss contributes to the upward trend in weather-related disasters and their damages in the United States [55].

According to the Enhanced Fujita (EF) Scale, the Midwest tornado was categorized as an EF-4 based on the damages observed after the event [31]. The EF scale ranges between EF-0 to EF5, where EF-0 refers to minor damage to buildings, and EF-5 correlates to immense destruction. After the disaster, multiple organizations get involved in relief work and assess the damage to the built environment. The Structural Extreme Events Reconnaissance (StEER) Network is one such volunteering organization, inducted by the Natural Hazards Engineering Research Infrastructure (NHERI), which helps determine the damage to disaster-impacted sites and was involved in the aftermath of the Midwest tornado.

2. Research Aim

This study aims to assess the performance of historical masonry structures through a data-driven methodology, to identify qualitative correlations between damage severity and building characteristics, such as the number of floors and proximity to the tornado, building materials, and the presence of retrofits. The on-site data gathered comprised information on building features, hazard particulars, and damage specifics of the buildings that were accessible. Since this work solely focuses on the historic masonry buildings of Mayfield, the remaining damaged buildings have not been reported. The research questions that are specifically addressed in this study are:

1. How did the different typologies of historic masonry buildings fare under tornadic loading?
2. How did the historic masonry structures with and without retrofit and additions perform compared to newer masonry constructions?
3. What do the results mean for preservation engineers in the aftermath of a similar disaster in a historic district?

3. Case Study: Mayfield and its historic masonry buildings

The town of Mayfield, Kentucky, was established in 1821 as a hub for government, social and commercial activities [39]. With the construction of the public square in 1824, the installation of railroads during the mid-1800s [34], and increased textile and tobacco business, the town expanded between 1875 and 1934. The town's historic downtown reflects various architectural nuances observed in Victorian and Classical masonry construction, a predominant construction technique used in the country between 1800 and 1940 [43]. As a result of this, and for demonstrating early signs of town planning, the historic district was added to the National Register of Historic Places in 1984. This registration was revised in 1996 to incorporate relevant surrounding buildings that contributed to the town's character and history [40].

Between 1860 and 1910, most of the buildings constructed in Mayfield utilized bricks as their primary construction material [39]. Since the bricks varied in size and were often fired unevenly, their quality and mechanical properties were inconsistent [33]. Like most constructions during this time period, Mayfield buildings were most likely constructed empirically [43]; this means that wind loading was only considered if the building height was one-and-a-half times the base. Over the years, the listed buildings have transformed in terms of the construction of additional sections, inserting new openings or sealing existing ones, and even complete demolition of some buildings. A prominent example of demolition is the row of buildings located on East South Street and included in the 1984 register. Their demolition was deduced from the previous Google Streetview [1] to have taken place between 2012 to 2019. As a result of the demolitions, only 34 buildings remained by the time the tornado occurred in December 2021.

The prevalent building typologies from the remaining 34 historic structures can be categorized into four groups; one-story, two-story, three or more storied, and unique structures, which are separated from the other for structural and cultural heritage purposes categories. The US Post Office in Mayfield was constructed in 1910 as a one-story structure, replacing its wooden-framed predecessor. Originally constructed as a classical revival building with marbled columns on its entryway and a detailed stone and brick parapet [39], the post office responded to the growing town. Following a fire in 1959, the post office underwent additions and structural retrofits to ensure its structural integrity [40]. During that process, two additional sections were built using concrete masonry units (CMU) and brick cladding to maintain the building's original historic aesthetics.

The most common structural typology observed in Mayfield downtown was the two-story structures. These were predominantly constructed around 1910 [39] and used as commercial spaces. The Merit Clothing Mill, located at the edge of the historic district, is the most prominent among the two-storied structures. As Mayfield grew, two of the country's largest clothes-production factories were erected in the town. Initially set up in a sewing room, the Merit Manufacturing Company moved into the two-story brick factory in 1900. This building portrays simple features like arched entrances, flat brick pilasters, and symmetric windows. In

1923, over 1 million people wore the clothes they manufactured, which generated multiple employment opportunities for locals in Mayfield [39].

Compared to the two-story structures, the three-story structures were fewer and sporadically spread throughout the town. Many of these resulted from the sudden influx of people traveling via Mayfield and the town's industrialization, like the Hall Hotel and American Legion. The Hall Hotel was built in 1930 with a brick-infilled concrete frame and termed the tallest structure in Mayfield, while the American Legion was the first brick-infilled steel-frame structure in town. Originally built as a three-storied structure, with two more floors added between 1910-1950, the hotel has been an integral part of Mayfield [39]. American Legion was built as a tribute to the soldiers from Mayfield and consisted of meeting rooms on the ground floor, a basketball court on the second, and a movie theatre on the second floor.

As mentioned previously, the final building typology of Mayfield included historic buildings built for specific uses and are termed unique structures. One of the most prominent landmarks in Mayfield is the Graves County Courthouse, located in the public square. This two-story brick structure with an impressive octagonal clock tower dates back to 1888. Before the current structure on-site, two other courthouses were constructed at this location; the first one, dating back to the early 1800s, was built as a log structure.

4. Data Collection and Processing Methods

The data collected for this qualitative analysis of damage in Mayfield following the Midwest tornadoes in 2021 was done in a two-phased approach. However, only the buildings assessed during the first visit have been explored as a part of this paper. The initial data capture in December 2021 was done by the Structural Extreme Events Reconnaissance (StEER) Network. StEER was founded in 2018 [20] as mentioned previously, is responsible for deploying volunteers for a coordinated damage assessment after an extreme event. The two-step reconnaissance initiated by StEER involves a virtual assessment followed by a field assessment of the damage. The Virtual Assessment Structural Team (VAST) performs the virtual assessment, which gets activated within a few hours of the tornado's (disaster's) touchdown. They collect relevant information about the disaster using multiple sources like social media and news channels to identify the impacted towns. This informs the next step, the Field Assessment Structural Team (FAST) mobilization for on-site damage assessment and collection of perishable data.

For the Midwest tornado, VAST was activated on 11 December 2021. The team gathered information from online video-sharing websites (e.g., Youtube channels) [54], social media sites (e.g., Twitter), newspaper articles [10,22,25], and weather reports to determine the impacted towns. These towns included Mayfield, Cambridge Shores, Princeton, Dawson Springs, Bremen, and Bowling Green in Kentucky. Subsequently, between the 12th and 16th of December 2021, the FAST team was deployed to investigate these towns and gather building-specific damage data. The authors, along with other volunteers with varying experiences and backgrounds, were a part of the FAST team deployed on-site. The team members were divided into smaller groups of 2-3 members per group, depending on the assigned task. They then utilized street-view cameras, unmanned aerial vehicles (UAVs), and door-to-door (D2D) assessment techniques to collect data and determine the extent of the damage from the tornado. At the end of each day, the teams would assemble to back up their data, update each other about their site conditions, and draft a written summary of their findings. The comprehensive report about the findings can be found by Roueche et al. [37].

4.1. Street View Camera for Panoramic Images

The surface panoramas (i.e., street-view imagery) were collected to visualize the damaged streets continuously. The NCTech iStar Pulsar+ street-view camera was set up on the top of a car to provide a 360-degree field view and capture images. The camera had a Global Navigation Satellite System that helped to geotag the locations of the images captured while traversing the streets. Since the camera had a high resolution of 12.3 megapixels (MP) and frequently captured frames every 4 meters (m), it ensured the continuity of the built environment. While gathering this data and passing through the impacted streets, the streets were also manually marked on a web mapping platform (i.e., Google Maps) to avoid image duplication and reduce the post-processing complexity.

4.2. Unmanned Aerial Vehicle for Aerial View

The Unmanned Aerial Vehicle (UAV) has proven to be an integral part of StEER's disaster response and has been used for multiple reconnaissance missions [20] since it helps to capture high-resolution images and provides a birds-eye view of the area. Prior to flying the UAV, permissions from the Federal Aviation Administration (FAA) were required. Obtaining the clearance from the FAA was challenging due to US President Biden's visit on 15th December 2021 and was only granted for a limited duration. The UAV used on-site was the SenseFly Ebee X [37], which was flown at an altitude of 230 feet in a double-grid pattern to cover the downtown.

4.3. Fulcrum for D2D Investigation

StEER used the door-to-door (D2D) methodology to investigate the impacted built environment in more detail. The building-specific data collected on-site was via a mobile application, Fulcrum, used by StEER [20]. Fulcrum [20] may be downloaded on phones and tablets and used for comprehensive data collection on-site. The pre-defined sections for building attributes, structural typology, images of different facades, and damage levels expedite the data collection process. Once the data is uploaded on Fulcrum, the application integrates with Google Maps to plot the damage levels of the surveyed buildings and visually confirm the damage extent.

4.4. Data Processing

The multimodal data collected was processed individually during the damage survey in Mayfield. The street-view data collected using the NCTech iStar Pulsar+ was stitched together to construct 360-degree panoramas, which can integrate with the Google Street View platform or Mapillary [20]. Mapillary is an internet application that allows users to upload their geotagged images and overlay them over the map, as seen in Fig. 4. Juhasz [18] compared Mapillary and Google Street View (GSV) to conclude that even though GSV offers higher coverage, the convenience and ease with which images can be added to Mapillary will help add inaccessible areas. The images collected using the UAV and the hand-held cameras were processed using Pix4D to generate point clouds and orthophoto maps. The images input into the software were tied to each other via ground control points, which help geo-reference the generated point clouds.

5. Results and Discussion

The damage to a structure during extreme wind loading is often a result of the increased internal pressure and the simultaneous

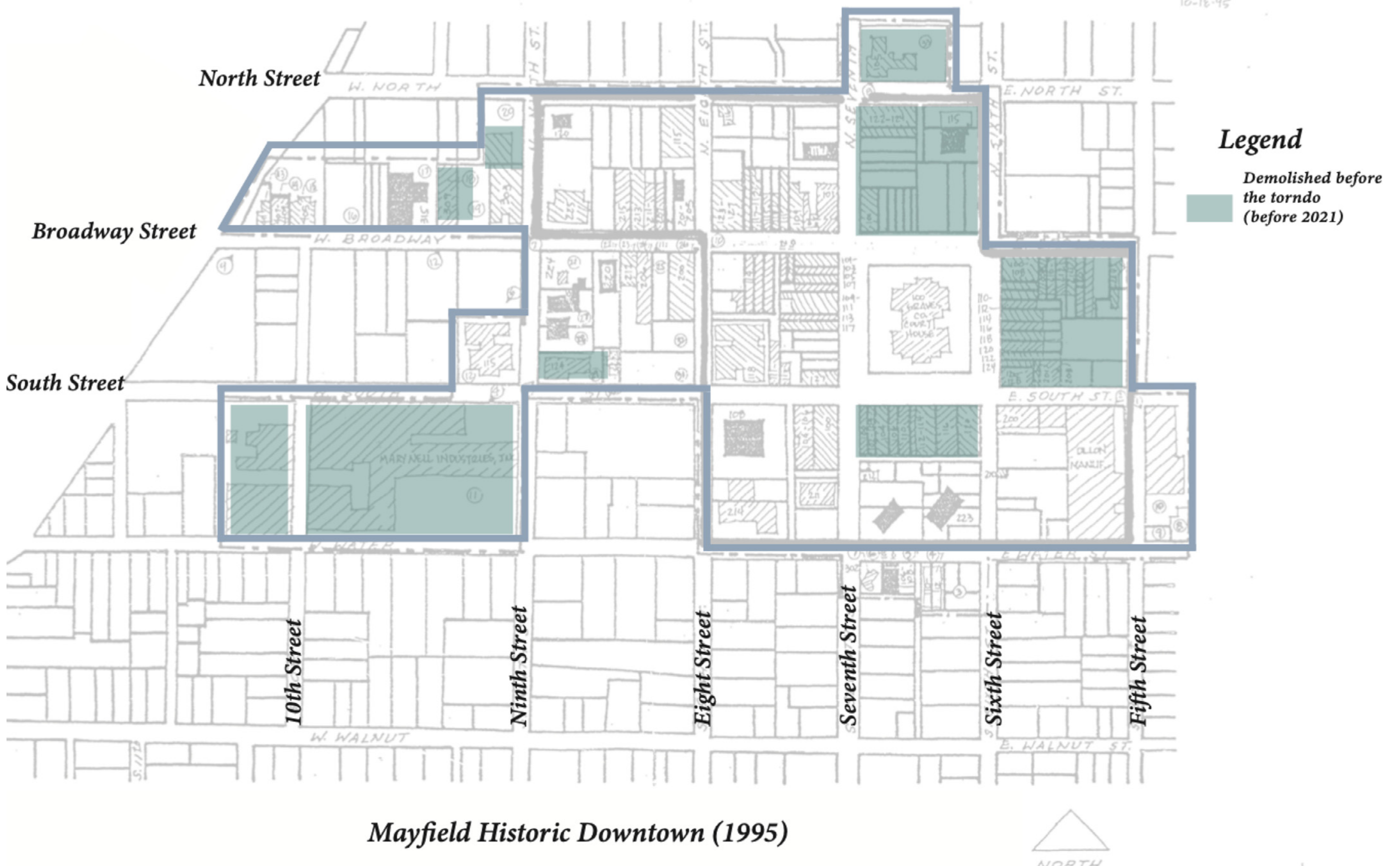


Fig. 1. The status of Mayfield downtown's historic buildings, December (based on the 1995 historic map).

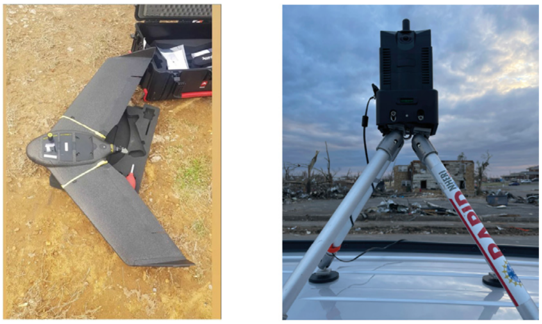
(a) One-storey Buildings: US Post Office

(b) Two-storey Buildings: Row building present on Broadway

(c) Three or more-storey Buildings: Hall Hotel

(d) Unique Buildings: Graves County Courthouse

Fig. 2. Representation images for the building typologies (Images extracted from Google Street View, Accessed March 2023).



(a) SenseFly Ebee X Drone (b) Streetview Camera

Fig. 3. On-site equipment used for data collection.

occurrence of lateral and uplift forces. These forces are resisted by the main wind force resisting system, which transfers them from the roof to the foundation through the walls. Even before a tornado comes in contact with the structure, the structure is often struck by flying debris, leading to a breach in the building envelope [52]. This breach escalates the internal pressure leading to a significant surge in the roof and wall loads, causing the weaker connections to fail and consequently resulting in the damage or removal of the roof. To summarize, the damages observed during extreme wind conditions are often a result of i) increased positive pressure due to high wind speeds, ii) increased negative pressure due to the reduced pressure at the center of the tornado, iii) wind-borne debris impact, or iv) structural instability caused by the wind forces [15]. The primary failure modes identified by Jordan [17] under extreme wind loading conditions are translations or sliding, overturning, lateral collapse, or material failure.

Previous tornadoes like the Tuscaloosa and Joplin in 2011 and Moore in 2013 caused extensive damage and hundreds of fatalities [28]. Prevatt et al. [41] inspected the damages to wooden residential structures following the tornadoes in 2011 and highlighted the need for constructing more resilient structures. A relevant point discussed by the authors was the impact on the community and its consequences like unemployment or long-term psychological effects. In the aftermath of the Tuscaloosa tornado, Lindt et al. [27] developed a dual objective-based design philosophy based on the damages observed on-site. According to this philosophy, the two design objectives for resilient structures include designing for damage (D) and life safety (L). To control damages caused by lower wind speeds, they suggested using connectors or improving load distribution while providing alternatives for life safety during higher wind speeds. Following the Moore tornado, Ramseyer et al. [44] proposed modifications for the residential structures to withstand an EF2 tornado, focusing on roof-to-wall connections and wall sheathing, and implemented them in 2014.

These prior studies for the tornadoes mentioned above have focused mainly on the damage and response of wooden residential buildings [44,47]. The repetitive damage patterns identified in these studies broadly included the roof-to-wall connections, wall-to-foundation connections, and discontinuity in the load path [24,36]. An initial study performed to identify the damages for masonry buildings was undertaken by Sparks [51], who concluded that maximum catastrophic wind damage occurs in low-rise masonry structures. While assessing damages to masonry structures after the 2021 tornado in Moravia, Czech Republic, Vejvara [56] observed damages to the leeward and unreinforced walls, failure, and displacement of roofs and collapsed ceilings due to the suction pressure.

The recurrent damages observed in Mayfield were identified using a combination of field notes, archival data, and the results of the processed data. The field notes and processed data helped to re-assess the buildings after returning from the disaster site. The archival research increased the author's comprehension of the structural progression, additions, and alterations, which may have impacted their behavior. The following sections highlight the overall damages seen in the historic buildings, followed by component-level damages. Even though multiple buildings were constructed within the same time period, they displayed varying levels of damage. Out of the 34 historic buildings at the time of the tornado, 11 were completely destroyed, and the remaining were assessed using the processed data from the techniques mentioned earlier.

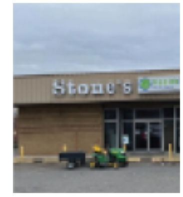
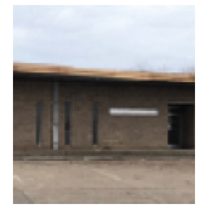
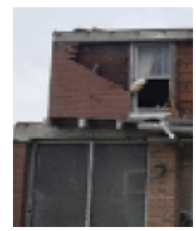
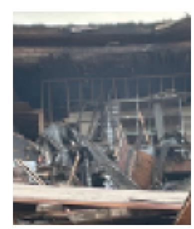
5.1. Overall Damages

With a majority of the historic masonry buildings constructed between the late 1800s and early 1900s, their primary structural system utilized load-bearing walls to transfer load [2]. The lack of reinforcement in these structural walls made them susceptible to extreme damage during lateral (horizontal) loading [30]. The overall damages were estimated using the Wind Assessment Guidelines [46]. Undamaged buildings referred to structures with no visible exterior damage, moderately damaged buildings were the ones where significant repairs would be required, even though their structural integrity was intact, and severely damaged buildings dis-

(a) Pointcloud (b) An example of the panorama (c) D2D buildings inspected

Fig. 4. The processed data after it's collection on December 2021.

Table 1
The damage levels observed in Mayfield and their description.

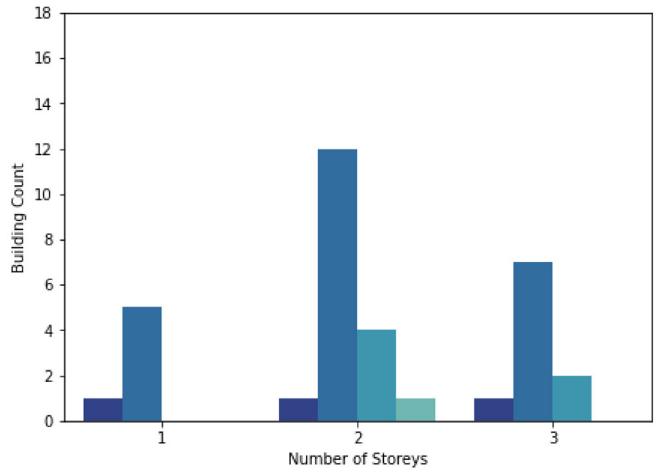
Damage Status	Description	Example
Undamaged	The structures displays no visible signs of wind damage.	
Minor Damage	Parts of the roof peeled off, damage to shingles, tree branches broken, and the damage is confined to the building envelope.	
Moderate Damage	The roofs are significantly damaged, houses shifted from foundations, broken windows and the building may require significant repairs.	
Severe Damage	Entire stories may be destroyed along with the roof and there are structural repairs required.	
Destroyed	Roofs and load-bearing walls undergo extreme damage depending on their proximity and the building may be left irreparable.	

played structural damages, which may or may not be repairable. The buildings classified as destroyed were the ones where there was a total loss of the structure, affecting the building beyond repair (Table 1).

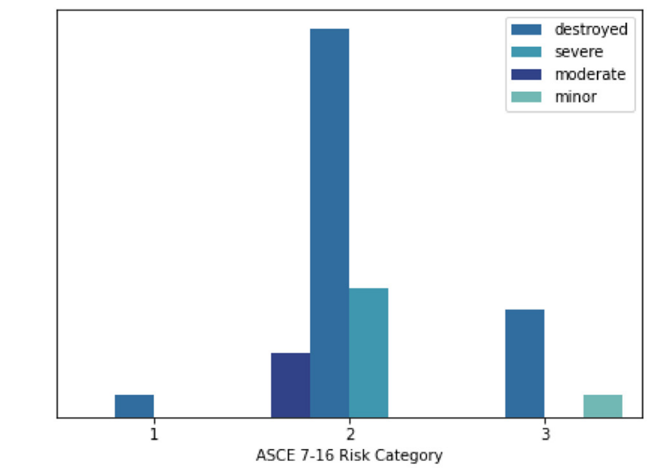
Table 1 showcases the different levels of damage in Mayfield. It is, however, important to mention that since the majority of the historic buildings were categorized as severely damaged or destroyed, the lesser damaged buildings are represented by, the newer constructions. The building-level damages observed in Mayfield were not only a result of their structural configuration but also dependent on the number of storeys, risk category, distance from the tornado, and its year of construction, as observed in Fig. 5.

The statistical results in Fig. 5 examine the relationships between the number of stories of a building, the risk category, the year of construction, and the distance from the tornado in light of the damage status. Evaluating these relationships helps identify commonalities between building features that were categorized as destroyed versus the ones that were classified as minor damage. These features can help inform future building codes or preservation practices. Since the number of stories and risk categories are categorical variables, categorical bar plots have been applied to the data to elucidate any relationships or trends. The year of construction has been depicted in terms of violin plots where the thickness of the violin illustrates the kernel density estimation (wider sections of the violin plot represent higher probability versus narrower sections which represent lower probability). The distance from the tornado is illustrated using a box plot due to the high spread of the data, indicating the distances at which the buildings were more heavily damaged.

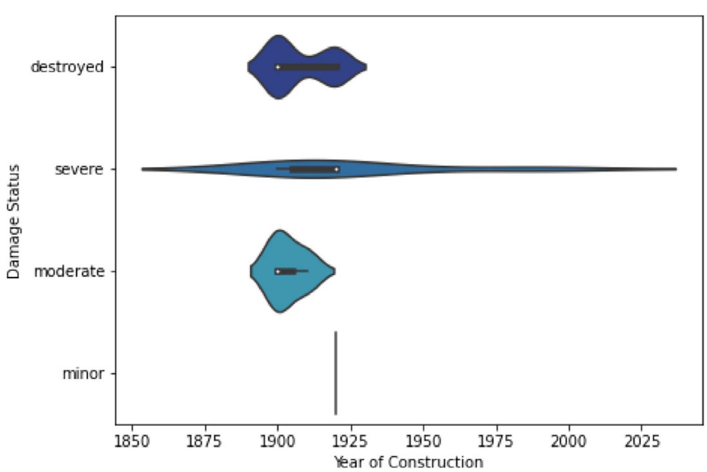
As illustrated in Fig. 5(a), while buildings with varying story numbers (1-3) suffered damage from the tornado, the documented single-story historic structures were either destroyed or severely damaged. Even though it is well known that the wind velocity increases with the height of the structure, the damage is also dependent on other factors, such as the structure's location with respect to the tornado's vortex [58]. Two-story historic structures exhibited the maximum variation in damage levels, which could be attributed to their higher density as compared to other building typologies. The damage levels of three-story buildings varied depending on the number of structures for which data was collected, but in general, they experienced moderate to severe damage. It is



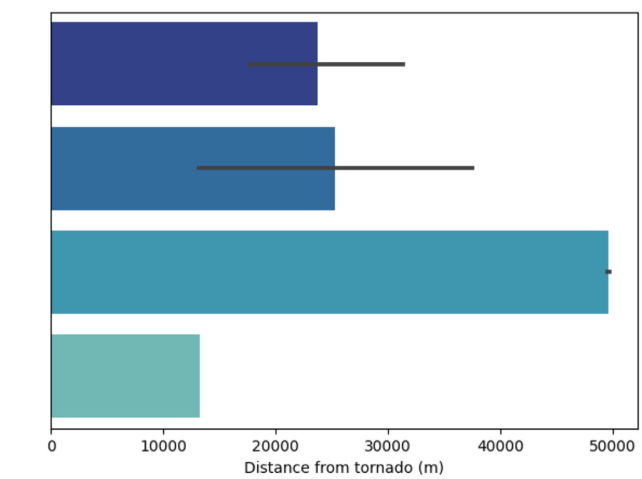
(a) Relationship between the Number of Storeys and Damage Status



(b) Relationship between the ASCE7-16 Risk Category and Damage Status



(c) Relationship between the Year of Construction and Damage Level



(d) Relationship between the Distance from the Tornado and Damage Status

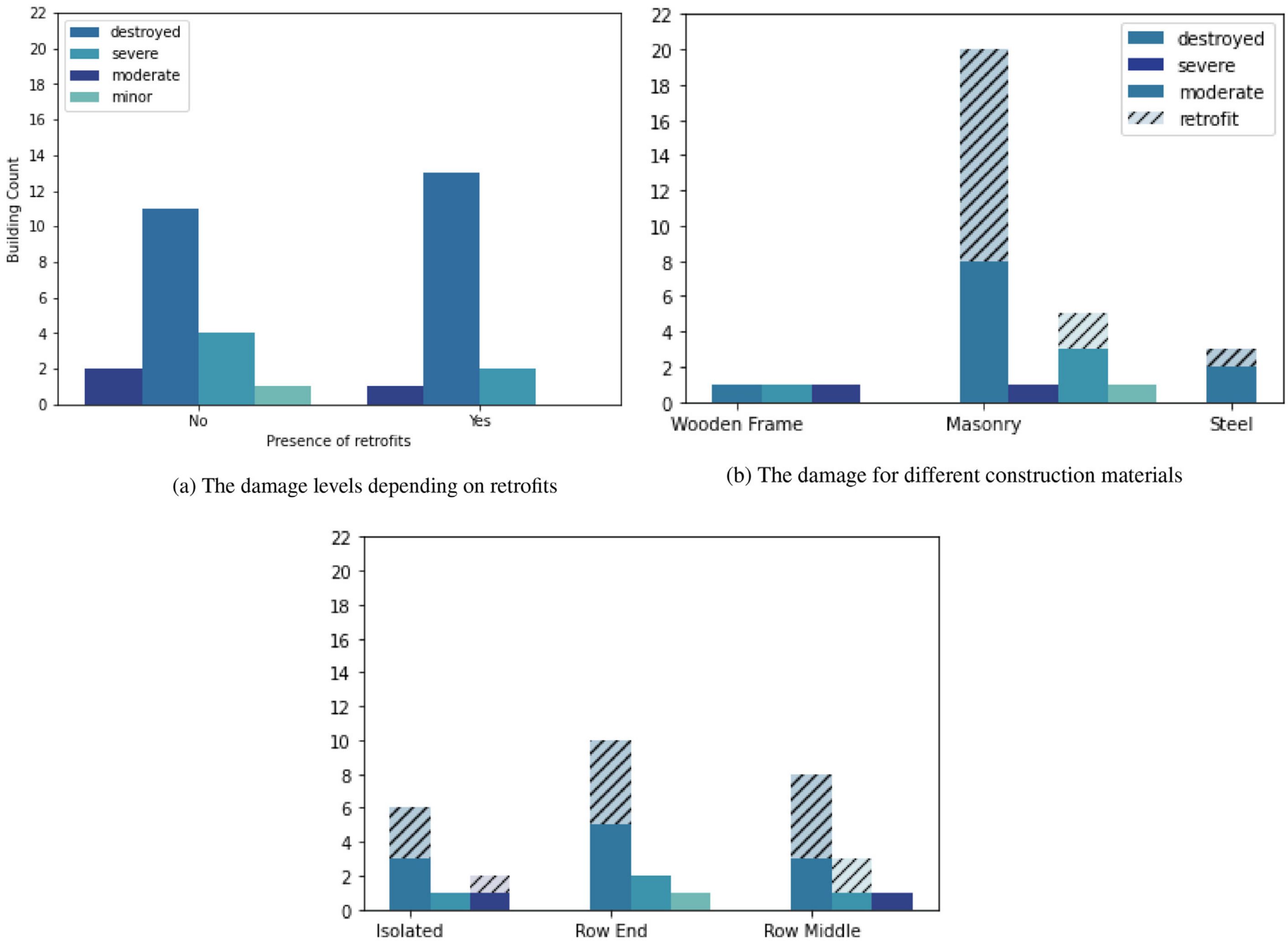
Fig. 5. Factors influencing damage levels for the historic buildings.

worth noting that the number of stories did not directly correlate with damage levels. A regression model with building status confirmed this as a dependent variable and the number of stories as an independent variable, which yielded a correlation coefficient of only 0.01. Thus, the findings support the hypothesis that the number of stories alone did not play a significant role in determining the damage status of historic structures.

The correlation between the ASCE Risk Category and damage levels in Fig. 5(b) shows a similar trend, where Risk II level buildings saw the most variation in damage status while the one Risk I building was destroyed, and a majority of the Risk III level buildings were also destroyed. The most recent updates to the American Society of Civil Engineering design standard (7-22) do not apply to Risk Categories I and II [5]. However, as seen in the dataset, Risk Category II comprises almost 80% of the historic structures, which under current standards, would not be updated for wind loading. As denoted in Fig. 5(b), historic structures that fall in Risk Category II buildings are particularly vulnerable and were mostly destroyed. This correlation calculated for this is 0.07, indicating a weak linear relationship and highlighting that other factors may influence the damage levels.

The violin plot in Fig. 5(c) illustrates that most of the historic buildings were constructed prior to 1925, before the implementation of any wind codes. The damages for these buildings ranged from moderate damage to destruction. The high variance observed for the destroyed and moderately damaged structures indicates heterogeneity of the data. However, it is essential to note that the shape can be affected by several factors, including the sample size and the data distribution. Since the data set utilized for this study was somewhat limited, the main takeaway from this correlation is that the older buildings showcased higher levels of damage.

The distance between the tornado and the structure plays a vital role in the extent of damage experienced by a structure. The tornado coordinates were extracted from the NOAA National Weather Service's storm prediction center, and the distance was calculated to each of the historic buildings using the haversine equation. However, it must be mentioned that there are existing biases within this data which may lead to approximations



(a) The damage levels depending on retrofits

(b) The damage for different construction materials

(c) The damages observed for different building settings

Fig. 6. The variation in damage levels based on structural attributes of the buildings.

while calculating the tornado path [11]. For example, Fig. 5(d) explores the relationship between the damage levels and the distance, where the structures located within 20000 m of the tornado were majorly destroyed, and the damage for the ones located between 20000 m to 50000 m varied between severely to moderately destroyed. This reinforces that the proximity of the tornado is proportional to the damage observed, with the closer structures undergoing higher levels of damage.

The overarching relationships between the number of stories of a building, the risk category, the year of construction, and the distance from the tornado were discerned to conclude that the distance to the tornado and the year of construction was the more relevant features. Following this, the presence of retrofit, the location of the building, and the structural material were explored to gauge the correlation between these more specific attributes.

As depicted in Fig. 6(a), the historic buildings showcased varying levels of damage irrespective of the retrofit's presence. It is interesting to note that even though a higher percentage of the historic buildings were retrofitted, a majority of them were classified as destroyed. Clearly, other factors, such as the proximity to the tornado, impacted the extent of the damage. An example in Mayfield highlighting this discrepancy was the two-story retrofitted structures on West Broadway versus those on N 7th Street, where the buildings were categorized as destroyed and severely damaged, respectively.

To highlight any underlying relationships between the construction type and the location of the buildings, categorical bar charts were generated. According to Fig. 6(b), the historic buildings were constructed out of wood, steel, or masonry. The wooden structures, known to be susceptible to wind damage, ranged from moderately damaged to destroyed over a normal distribution. Similarly, the steel frame buildings, while frequent, also have normal distribution across the damage status. Considering the sharp drop-off of the unimodal distribution, it can be concluded that the masonry structures were consistently destroyed. Thus, based on the unimodal distribution, it can be concluded that masonry buildings were the most vulnerable during the Midwest Tornado in Mayfield.

As concluded from the previous paragraphs, there was not one specific feature that influenced the extent of the damage but an amalgamation of all of them. Based on Fig. 6(b) and Fig. 6(c), there were a higher number of retrofit masonry structures as compared to wooden or steel, and they still underwent varying damage levels. The US Post Office, a retrofitted historic structure located a few

(a) Icehouse Gallery: Destroyed

(b) US Post Office: Moderately Damaged

(c) Row Buildings on Broadway: Destroyed

(d) The isolated two-storey structure: Severely Damaged

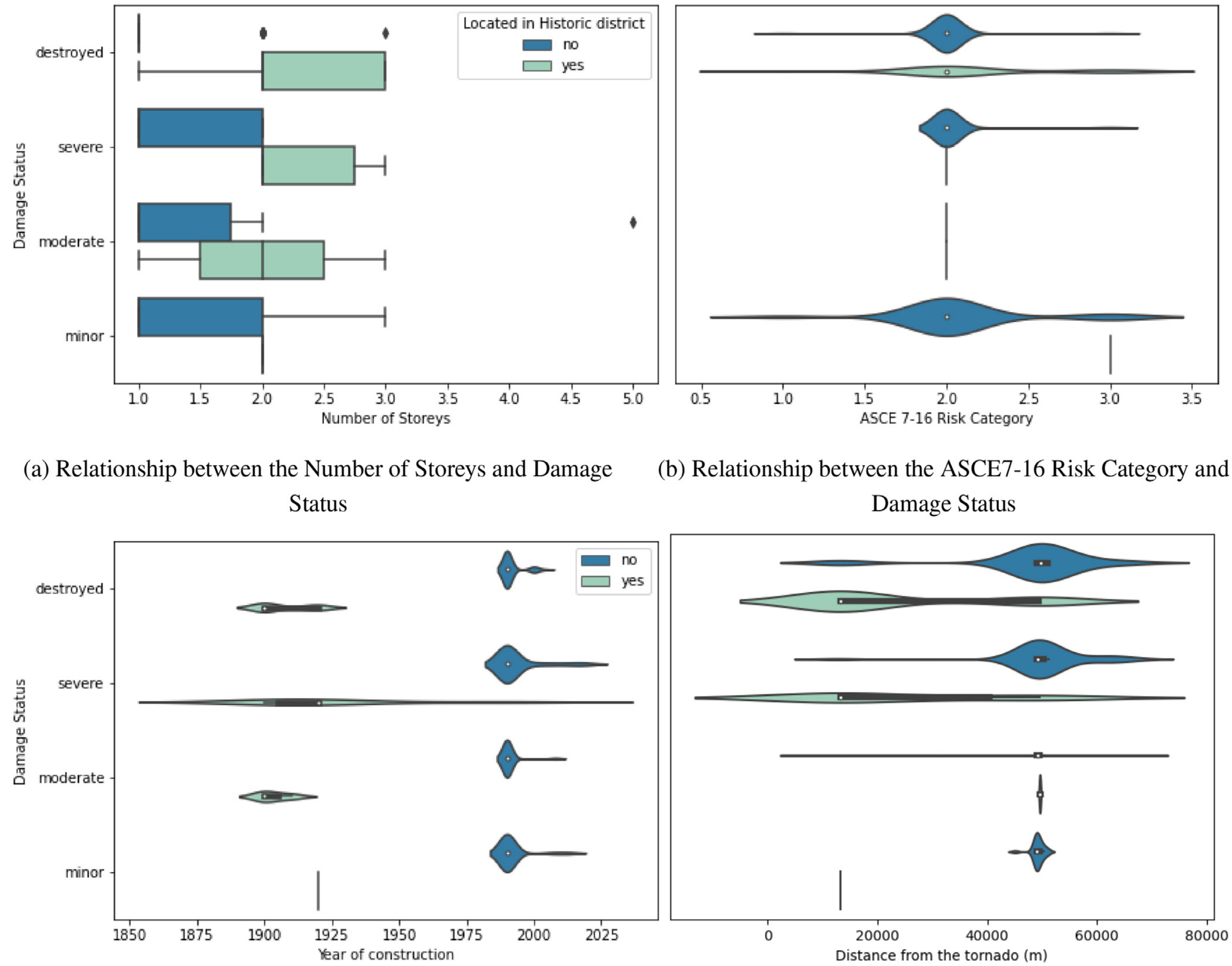
(e) Damage to the American Legion: Severely Damaged

(f) Damage to the Hall Hotel: Severely Damaged

(g) Damage to the Methodist church: Destroyed

(h) Damage to the Graves County Courthouse: Destroyed

Fig. 7. Variation in damage observed for historic structures.



(a) Relationship between the Number of Storeys and Damage Status

(b) Relationship between the ASCE7-16 Risk Category and Damage Status

(c) Relationship between the construction year and damage status

(d) Relationship between the Tornado distance and Damage Level

Fig. 8. Comparison between damage levels of historic and non-historic structures.

meters from the tornado path, experienced damage limited to the walls and roof and was classified as moderately damaged. While the other retrofitted one-storey structure was the Icehouse Gallery, which was described as destroyed even though it was located further from the tornado's path. This illustrates the variation in damage levels irrespective of the retrofit status of the structure. Thus, not considering their retrofit levels, the distance from the tornado significantly affected the damages observed.

The two-story structures located at varying distances showcased varying levels of damage as observed in Fig. 5(a). With the majority of them were located within a few blocks from the tornado's path, and entirely destroyed, making it challenging to decipher specifics about the building, including whether they were retrofitted or not. For the two-story row buildings, the end buildings demonstrated higher levels of damage than the middle ones (6(c). The structures located farthest from the tornado were the three-story structures, as compared to the other typologies. The Hall Hotel and American Legion were located at different distances from the tornado and were classified as moderately and severely damaged. The hotel's roof was significantly damaged but looked structurally sound. While the American Legion was severely damaged, with its rear section completely collapsed and deemed unusable. Some of these examples are illustrated in Fig. 7.

5.2. Implications of Findings for Preservationists

To assess the response of historic and non-historic buildings to tornadoes, a comparison was made based on several factors, including the number of storeys, risk category, distance from the tornado, and year of construction. The relationship between these factors was examined using the bar plot and the violin plot. The results showed that, regardless of these factors, historic buildings consistently suffered significant damage and were frequently classified as destroyed.

Fig. 8 (a) shows that, in the immediate vicinity of the tornado, in comparison to the historic structures, the non-historic structures were limited to two-stories or lesser. Notably, severe damage was the most significant damage observed in non-historic buildings, while many historic buildings of similar typologies were destroyed. On examining the relationship between the risk category and the damage levels (Fig. 8(b)), historic and non-historic buildings were primarily associated with risk category II. This emphasizes the need to incorporate this specific category in the upcoming building codes to enhance their wind load capacity and is currently missing from the ASCE 7-22 design standard. In a study by Pipinato [38], the tornado-resistant capacity of various building typologies were investigated based on historic tornadoes in Italy. This study found that masonry buildings could withstand a maximum of an EF3 intensity tornado, and anything greater than that would result in severe damage.

As depicted in Fig. 8(c), newer buildings were constructed in the late 1900s, and both historic and non-historic buildings experienced damage ranging from minor to destruction, regardless of their year of construction. It is pertinent to mention that a higher number of historic structures were destroyed, while the non-historic ones showcased minor damage more frequently. Additionally, it must be noted that the non-historic buildings were also located further from the tornado, as seen in Fig. 8(d), which may be a reason for the lower damage levels.

The findings of this study have important implications for future preservationists regarding the protection of historic structures during tornadoes. It is evident from the results that historic buildings are more vulnerable to damage during tornadoes, even when compared to newer buildings of similar types. Therefore, preserving historic structures during extreme weather conditions such as tornadoes requires additional measures to be taken to protect them. One of the main ways to mitigate this damage is retrofitting older structures to enhance their wind load capacity. A study based on the aftermath of the Jefferson tornado in 2019 suggested the use of innovative retrofit techniques to enhance the structural stability of historic structures against extreme wind conditions [14].

Even though multiple grants are available from the federal government [7], National Parks Service, and Federal Emergency Management Agency (FEMA) for rehabilitating impacted historic structures, they are often highly competitive and rarely cover the total necessary expenditure. Given this, most owners find it more feasible to demolish the historic buildings, to construct a newer and more resilient structure than repair it [29].

After conducting the December reconnaissance, the Kentucky heritage council was contacted to assess possible restoration plans for the historic buildings in Mayfield. In conjunction with the FEMA, the heritage council identified historic buildings that could be restored, the ones they could attempt to restore, and those which were already demolished or beyond repair. Although the council and FEMA determined that around 15-18 structures could be restored, unfortunately, the owners chose to demolish the structures. Based on the December visit, only three historic buildings, the Hall Hotel, the US Post Office, and the Clothing mill, were being considered for rehabilitation. Regrettably, there are no restrictions on what owners can do to their property, including demolition, even if the property is listed as historic [7]. Therefore, it is imperative to retrofit and strengthen historic buildings to ensure their preservation and longevity.

6. Conclusion

This paper highlights the vulnerability of historic masonry structures in the aftermath of the December 2021 tornado in Mayfield, Kentucky. Perishable damage data was collected by a reconnaissance team and re-evaluated with building-specific details to analyze the qualitative relationships between damage levels and building attributes. Multiple failure modes were observed in the masonry, consistent with findings from other tornado sites.

The results show that historic buildings suffered varying levels of damage, ranging from moderate damage to destruction, while non-historic buildings fared better on average. This disparity is attributed to several factors, including the year of construction, structural system, and distance from the tornado path. Distance from the tornado path was found to be a critical factor in the observed damage levels. Although located near the tornado, retrofit buildings performed better, but the available data needed to be more exhaustive to make conclusive claims.

The correlations presented are based on limited data, and further research is needed to establish comprehensive relationships between different variables. More specific data on historic buildings is required to determine the cause-and-effect relationship between damage levels and building attributes. Therefore, future research includes compiling various datasets for historic buildings to assess the relationship between building attributes and tornado damage levels.

Data Depot

The data utilized for this study is available on the DesignSafe Data Depot, under the same title [19] located at https://doi.org/10.17603/ds2-zwg3-nv98 (Last Accessed: May 11, 2023).

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Appendix A

Typically, roof failure begins with the increased internal pressure which results from sheathing material failure or a breach in the building envelope. Razavi et al. [45] experimentally compared the uplifts that different roofs may incur, only to conclude that flat roofs experience maximum uplift and shear as compared to gable or hip roofs.

Table 2, in appendix A, illustrates the different types of roof and the levels of damage sustained. The prevalent roof system observed in Mayfield were flat roofs with wooden rafters, and were majorly seen in buildings classified as destroyed (Fig. 2). The roof-specific damages included the loss of sheathing, missing roofs and damage to the substrate and roof structure. The US Post Office and Hall Hotel are examples of buildings that underwent sheathing failure, which also led to water ingress. The limited capacity of the roof to wall connections, and possibly their age, culminated in their poor performance during extreme wind conditions and impacted both the roof and walls. The historic buildings that were retrofitted with anchors in the recent years were completely destroyed to making it impossible to gauge their role during the Midwest tornado (Fig. 9).

(a) Roof Collapses (b) Loss of sheathing (c) Minor damages to the roof

Fig. 9. The different roof damages observed in Mayfield.

Table 2
Relationship between the roof shape and damage levels.

0	5	10	15	20

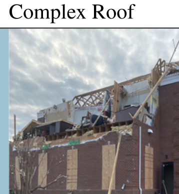
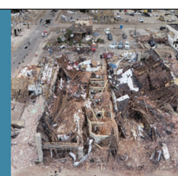
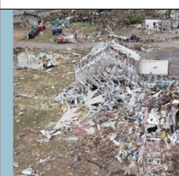
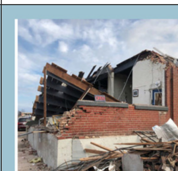
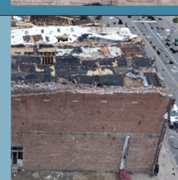
	Complex Roof	Flat Roof	Gable Roof	Hip Roof
Destroyed				
Severe Damage				
Moderate Damage				
Minor Damage				

Table 3
Relationship between the roof MWFRS and damage levels.

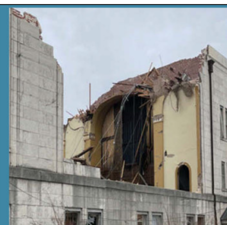
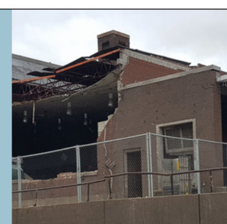
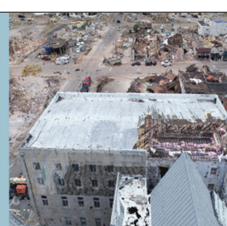
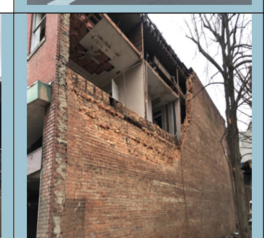
	Wooden Diaphragm	Steel Diaphragm	Unknown
Destroyed			
Severe Damage			
Moderate Damage			
Minor Damage			

Table 4
Relationship between the wall MWFRS and damage levels.

0	5	10	15	20

	Wooden Diaphragm	Concrete Diaphragm	Unknown
Destroyed			
Severe Damage			
Moderate Damage			
Minor Damage			

Appendix B

Wall failures for wind-impacted structures often depend on the loss of the roof and it is connections to the roof or foundation. A strong correlation was observed between an extensively damaged roof and its impact on the load-bearing capacity of the wall. The impacted walls depended on the direction of the tornado or the wind-borne debris, leading to damaged cladding without altering the current load path. For structures whose roof's structural system was still intact but had a loss of sheathing, there was lesser damage to the walls. The table below provides additional qualitative data highlighting the relationships between the damage levels and wall MWFRS (Fig. 10).

(a) Wall structural system exposed (b) Partial of wall collapse (c) Wall collapse

Fig. 10. The different wall damages observed in Mayfield.

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