# Three-Dimensional Digital Documentation of Tornado-Damaged Heritage Buildings

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**Abstract:** In December 2021, an EF-4 tornado swept through several Midwest states in the United States, with Kentucky being the worst hit. Among the impacted towns was Mayfield, KY, where the historic buildings in downtown suffered significant damage. In response to this disaster, the authors conducted a reconnaissance mission to digitally document the affected historic structures. This involved capturing a series of three-dimensional (3D) point clouds, providing detailed spatial data about the impacted buildings. The resulting data set includes both the original raw data and processed information, now accessible via the DesignSafe open-access repository. This paper outlines the data collection process for the impacted buildings, and the steps undertaken to process it. The final product of this endeavor are the point clouds generated for the historic building typology, which included 10 historic buildings and 2 comparable religious buildings. These point clouds serve as invaluable resources for further analysis, aiding in understanding a disaster's impact, and guiding restoration endeavors.
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## Introduction

The devastating impact of tornadoes on the built environment has been a long-standing concern, with the United States alone experiencing almost a thousand tornadoes each year (Brooks et al. 2014). The impact of tornadoes on the built environment has been explored extensively for wooden and residential constructions (Roueche and Prevatt 2013; Standohar-Alfano and van de Lindt 2016; Roueche et al. 2024), but their impact on older structures is comparatively lesser studied (Kaushal et al. 2023c). In a study by Zanini et al. (2017), the authors reviewed the impact of the *Rivera del Brenta* tornado on different building typologies and concluded that the damages in the older masonry building stock were higher in comparison to the reinforced concrete ones. Similar observations have been made during post-tornado reconnaissance missions in the United States, where low-rise masonry structures (Sparks et al. 1989) and historic structures (Wood et al. 2020) were seen to be susceptible to extensive damage.

In December 2021, a tornado outbreak occurred in the Midwest region of the United States and notable damages were documented across Arkansas, Missouri, Tennessee, and Kentucky (Pilkington et al. 2021). This off-season tornado outbreak was influenced by the higher-than-average temperatures, and covered a distance of over 250 mi (Pappas 2021) at a speed of 94 mph (Samenow 2021). Among the impacted states, Kentucky (KY) underwent devastating damage (Schreiner and Dylan 2021), where the tornado was classified as an EF-4 tornado (McDonald et al. 2010).

The town of Mayfield in Kentucky, documented in the National Register of Historic Places (1984), was established in 1821 and served as a central hub for government, social and commercial activities. Its growth was facilitated by key developments, such as building the public square in 1824, introducing railroads in the mid-1800s, as noted in Munday (1925), and the flourishing textile and tobacco industries, leading to a notable expansion between 1875 and 1934. Recognizing its historical significance and early town planning efforts, the downtown of Mayfield was added to the National Register of Historic Places in 1984 (National Register of Historic Places 1984). This was subsequently updated in 1996 to encompass additional nearby structures that contributed to the town's character and historical value, as recorded in the National Register of Historic Places (1996).

In recent years, digital documentation has emerged as an essential tool for recording and evaluating post-disaster damage (Kallas and Napolitano 2023; Dai et al. 2011). With the advancement of surveying technologies, the utilization of high-resolution 3D data capture has become pivotal in surveying and documenting sites to facilitate damage assessment (Cavalagli et al. 2020), structural evaluation (Pepe and Costantino 2021), and as a foundation for numerical simulations (Ursini et al. 2022; Castellazzi et al. 2022). These methodologies typically employ both photogrammetry and Light Detection and Ranging (LiDAR) techniques, employing geomatic approaches to gather spatial data about structures. While LiDAR is often considered more precise (Meng et al. 2010), when used in conjunction with photogrammetry, they enhance precision in measurements (Baltsavias 1999). Moreover, these techniques have been extensively utilized for documenting historic structures and gaining insights into their structural behavior (Cuadros-Rojas et al. 2024; Kaushal et al. 2023b). However, despite the widespread application of digital documentation techniques for heritage structures affected by disasters, there remains a gap in their deployment in tornado-affected areas.

Following the Midwest tornado, a comprehensive two-phase reconnaissance mission was coordinated to gather damage data from

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the impacted areas and understand the behavior of historic masonry building structures. The initial data collection occurred in collaboration with the Structural Extreme Events Network (StEER), concentrating on assessing the damage extent in Kentucky in December 2021. Given that almost 82 structures were listed as relevant in both the National Register listings, only 34 existed before the tornado occurred and could be broadly categorized into one-story structures, two-story structures, three or more storied structures, and unique structures (Kaushal et al. 2023c). These historic structures were constructed in the early to mid-1900s, primarily as masonry structures (National Register of Historic Places 1984). The second mission, conducted in March 2022 focused on digitally documenting the remaining historic building structures within the affected town. By that time, only 10 (+2 new religious building typology) could be documented, as the rest had already been demolished due to the damage incurred. This paper delineates the steps employed for documenting these structures using photogrammetry and LiDAR techniques, elucidating the corresponding processing steps. Additionally, the locations for accessing the final models is also highlighted.

## Data Acquisition Campaign

As previously mentioned, the geometric data for the remaining historic buildings in downtown Mayfield were collected in March 2022. For the surviving buildings, this paper provides a detailed account of their documentation using photogrammetry and LiDAR techniques. It is important to note that none of these structures had been documented previously. The data obtained through these methods has been organized and presented in a tabulated format, as shown in Table 1. This table highlights not only the historic buildings but also includes two additional residential structures that underwent documentation.

### *Aerial Photogrammetry*

During the fieldwork, unmanned aerial vehicles (UAVs) were employed to capture aerial imagery of each historic structure. The ability of UAVs to gather large-scale data along with high-resolution imagery has previously been leveraged for reconstruction (Zheng et al. 2018). The DJI Matrix (DJI X5S) was flown approximately 20–40 m above each structure to ensure comprehensive coverage. Moreover, flights were conducted using both a grid-like pattern and a circular pattern to collect images for the future construction of a point cloud. The Pix4DCapture flight app to design the drone flight and image captures in Mayfield (PIX4D 2022). The app (i.e., computer application) uses mission settings such as flight altitude, overlap, camera type, camera angle, and drone speed to create the best image capture waypoints in a flight path, thus taking images over specific time intervals. These time intervals varied with each flight, but in general, the mission set included an oblique camera angle at 60 degrees, 80% overlap, and the normal drone speed.

In addition to capturing aerial imagery, an extra measure was implemented to establish spatial connections among the images. Ground control points (GCPs) were specifically identified for this purpose. These GCPs serve as distinct and recognizable targets on the ground, facilitating the scaling and orientation of images concerning their global positions through GPS coordinates. In this project, the selection of GCPs was diverse, ranging from utilizing road markings to placing preprinted markers near the structures. In total, 49 GCPs were employed for Mayfield, and coordinates were established for all four corners of the documented structure.

**Table 1.** The data collected for each of the buildings

| Building name | Aerial photographs | Camera photographs | LiDAR scans |
|---|---|---|---|
| D2D Building | 441 | 968 | 11 |
| Clothing Mill | 450 | 4,421 | 14 |
| Hall Hotel | 855 | 646 | 8 |
| Mayfield Mural | 414 | 413 | 7 |
| Urban Outfitter | 362 | 2,483 | 7 |
| Damaged Row | 325 | 554 | 6 |
| New Vision Church | 137 | 1,130 | 7 |
| AME Church | 209 | 1,994 | 8 |
| Ice House Gallery | 454 | 1,054 | 7 |
| US Post Office | 347 | 1,586 | 8 |
| Court House | 348 | 361 | 10 |
| American Legion | 517 | 253 | 8 |
| Residential 1 | — | 242 | — |
| Residential 2 | — | 60 | — |

### *Terrestrial Photogrammetry*

In addition to aerial photogrammetry, terrestrial photogrammetry was conducted using Leica P50 and RTC360 Leica scanners, along with a handheld Canon camera. The Leica RTC360 scanner was specifically utilized to capture the external facades of the majority of structures, while the Leica P50 was exclusively deployed for the courthouse and internal spaces. This decision was guided by the RTC360 scanner's capabilities, which include the accurate capture of image data at an impressive rate, the generation of a point cloud in under two minutes, and its convenient portability (Biasion et al. 2019). Conversely, the Leica P50 covers a larger distance of up to 1 km and provides high-quality 3D data and HDR imaging, with an exceptionally high-speed scan rate of 1 million points per second. Given its slower scanning pace compared to the RTC360, the P50 was selectively used in specific locations (Leica Geosystems 2022b).

The scanners were strategically positioned at all the corners and midpoints of the structures, complemented by the use of Canon camera imagery to overcome the limitations associated with UAVs, particularly their minimal coverage of building facades since they were not flown along the facades. This combined approach aimed to construct a comprehensive photogrammetry model. In addition to this, the Global Navigation Satellite System (GNSS) was enabled to identify the geospatial location for all the scans and help create a highly accurate point cloud. A summary of the data specific to each building is presented in Table 1.

## Data Processing

Following the collection of data, a three-step methodology was utilized to process the gathered information, where the images and scans were transformed into point clouds, as shown in Fig. 1. The first two steps involved individual processing of the UAV images and LiDAR scans to generate the point clouds, and the third step combined the two point clouds. This process entailed the independent management of data acquired from diverse sources, as detailed in the subsequent sections.

### *Aerial Photogrammetry*

As observed from Table 1, the number of images collected using the UAV ranged between 130 and 1,500, depending on the area of the structure. These images were processed using a photogrammetry software called Pix4D (PIX4D 2022). The UAV images were inputted into the software, initiating a three-step processing sequence



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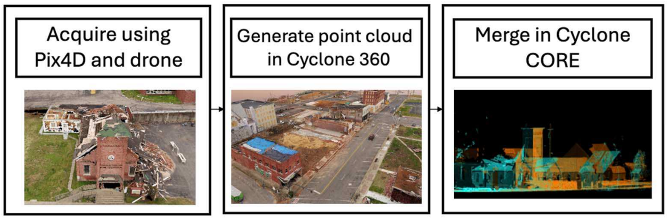


**Fig. 1.** An overview of the data collection and processing methodology.

to generate the point cloud. In the first step, termed "initial processing," the images were spatially arranged based on their associated GCPs, with a minimum of four GCP points used for 3D orientation. The subsequent two steps, "point cloud and mesh" and "DSM, Orthomosaic, and Index," were executed within the software automatically, resulting in the final model with minimal manual intervention. It is noteworthy that, for certain structures, portions of the point clouds generated by Pix4D were incomplete, attributed primarily to reflective surfaces or limitations in UAV-captured images.

### *Terrestrial Scanning*

The LiDAR scans were brought into Leica's Register360 to align them and generate the point cloud. The Leica scanners, working in tandem with Register360, provided the benefit of automatic links connecting different scans, hastening the spatial identification of each scan's capture location. Ensuring an overlap of more than 99.5%, each pair of scans was aligned, but for significantly damaged structures, the overlap decreased to 85%. The alignment process encompassed both horizontal and vertical adjustments, and then followed by optimization and bundling to secure the final output.

### *Merging the Point Clouds*

The primary reason to combine the point clouds for digital documentation is to build more comprehensive point clouds, which can be more precise than using a single point cloud. One of the approaches to merge UAV and LiDAR data is by implementing the registration technique, which iteratively aligns corresponding points to build the complete 3D model (Besl and McKay 1992). Once the point clouds were processed individually in the abovementioned software, Cyclone (Leica Geosystems 2022a), was used to merge the individual point clouds. This helped process the data, register the two point clouds to each other, and then fuse it into a full 3-D model. Figs. 2 and 3 are representative of the individually processed point clouds, while Fig. 4 was the final point cloud.

To assess the errors or misalignment between the two point clouds, the Cyclone software was employed to compute the Euclidean distance between corresponding points within the point cloud data sets. Subsequently, the errors were quantified using the mean squared error (MSE) as the chosen metric. These metrics serve as a comprehensive measure of the disparities between the point clouds and are presented in Table 2.

## Organization of Data Files

The data collected as a part of this research are available on DesignSafe, and easily accessible under the project number PRJ-3417 (Kaushal et al. 2023a). Currently, the data are divided into Raw Data, Processing Data, and Deliverables, and explained in the following subsections.

**Fig. 2.** The point cloud for the Post Office (USPS) generated by Pix4D (USPS).

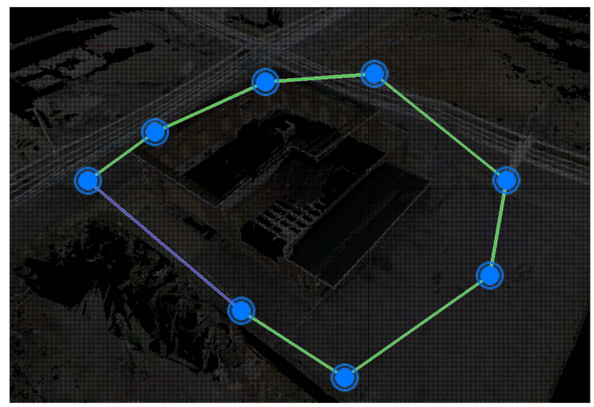

**Fig. 3.** The LiDAR scans aligned in Register360 for the Post Office (USPS).

**Fig. 4.** The final point cloud for the Post Office (USPS).

**Table 2.** The final errors while merging the two point clouds

| Building name | Wall 1 (mm) | Wall 2 (mm) | Wall 3 (mm) | Wall 4 (mm) | Roof (mm) |
|---|---|---|---|---|---|
| D2D Building | 8 | 31 | 19 | 43 | 2 |
| Clothing Mill | 20 | 22 | 16 | 21 | 3 |
| Hall Hotel | 29 | 6 | 24 | 21 | 17 |
| Mayfield Mural | 12 | 7 | 8 | 8 | 5 |
| Urban Outfitter | 6 | 21 | 7 | 13 | 4 |
| Damaged Row | 8 | 7 | 18 | 19 | 18 |
| New Vision Church | 24 | 33 | 30 | 32 | 11 |
| AME Church | 10 | 25 | 40 | 20 | 30 |
| Ice House Gallery | 9 | 16 | 16 | 12 | 36 |
| US Post Office | 25 | 50 | 17 | 6 | 7 |
| Court House | 17 | 3 | 28 | 11 | 4 |
| American Legion | 9 | 3 | 14 | 3 | 11 |

(a) (b) (c)

**Fig. 5.** Examples of the point clouds available in the data set: (a) Clothing Mill; (b) Hall Hotel; and (c) Mayfield Mural Building.

### *Raw Data*

After gathering the data on-site, it was transferred to a designated folder, accessible through the respective device name that was used to collect it. The folder titled as *Cannon* holds the images from the handheld camera, the *RTC* folder contains the scans from the terrestrial scanner, and the *GNSS* folder has the coordinates corresponding to the markers used to geolocate the structures. Within this main folder, there is a subfolder named *Sorted*, where the raw data is further organized into folders corresponding to different buildings. These folders contain photographs captured through both UAV and handheld cameras in JPEG format, and the individual terrestrial scans are housed within the main folder.

### *Processed Data*

The processed data directory is structured according to the specific software employed for data processing. As previously mentioned, Pix4D was utilized to generate point clouds from the data collected by the UAV, with these point clouds being stored in the Pix4D folder. Similarly, data collected using the LiDAR scanner and the corresponding generated point clouds are stored in the Register360 folder, while the merged point clouds are located in the Cyclone folder. It is essential to note that although these folders house processed data, the point clouds contained within can only be utilized within their respective software environments for exploration by other researchers, should the need arise.

### *Deliverables*

The most significant directory within the data set is the *deliverables* folder, particularly valuable for those seeking to leverage the point clouds further. This folder encompasses point clouds generated by each software in their most reusable formats, identified by the '.pts' and '.las' extensions. These point clouds, exported from their respective software, represent incomplete data sets and are present under *Pix4D, Register360*, and *Cyclone* folders. For comprehensive usability, the *final PC* folder stores the fully merged point clouds, complete with '.las' and '.pts' extensions, offering a reusable resource if needed. These final point clouds are easily editable and accessible using all photogrammetry software that supports these extensions such as *CloudCompare* (Girardeau-Montaut 2016) or *Metashape* (Over et al. 2021). Fig. 5 displays a few of the point clouds available in the data set.

### *Data Reusability*

Researchers in the fields of structural engineering, architecture, and heritage preservation can leverage the data set to conduct in-depth analyses of the structural behavior of historic masonry buildings under extreme wind loads. By examining the detailed 3D point cloud models of the tornado-damaged buildings in Mayfield, Kentucky, researchers can gain insights into how different architectural features and construction materials respond to high wind velocities and dynamic loading conditions (Kaushal et al. 2023b). This analysis can provide valuable information on failure mechanisms, such as wall collapse, roof uplift, and foundation failure, allowing researchers to identify vulnerabilities in historic masonry structures and develop targeted retrofitting strategies to enhance their resilience to future tornado events. Additionally, machine learning algorithms can be leveraged for image segmentation purposes, where this data may serve as a training or testing data set (Barrile et al. 2019).

## Summary

In recent years, there has been an increase in the adoption of digital documentation techniques across various domains. These methodologies have eased the process of recording information about existing structures and those affected by disasters, offering valuable architectural and structural insights. In specific situations, these techniques have been applied for rapid damage assessments and emergency interventions.

This paper focuses on the digital documentation of historically significant structures in Mayfield, KY, which were impacted by the tornado in December 2021. Notably, this marks the initial implementation of digital documentation for the historic structures in Mayfield post-tornado. Due to the demolishing that took place in the aftermath of the tornado, only 10 historic buildings and 2 churches could be documented, and are representative of the prevalent typology of historic buildings observed. Some of the internal spaces within these structures were inaccessible due to safety reasons, hence only the clothing mill and the hall hotel could undergo internal scanning. The resulting point clouds primarily represent the external envelope of the structures and is a limitation of the current work. A postprocessing challenge that arose was from the inability to integrate images from the handheld camera into the point clouds due to an error in the camera settings, rendering their incorporation into the models challenging.

This was resolved considerably by combining the terrestrial scans and the aerial photography.

The digital documentation of Mayfield serves as an example of how post-disaster buildings can be documented to comprehend the devastating impact of events like tornadoes. The resultant point clouds are currently employed to analyze various failure modes in historic buildings during tornadoes. The authors anticipate that these point clouds will prove valuable to the research community, enhancing an understanding of the realm of tornado-structure interactions.

## Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. The raw, processed, and final data mentioned in this study is available on DesignSafe repository under Project No. PRJ-3417 (https://www.designsafe-ci.org/data/browser/public/designsafe.storage.published/PRJ-3417).

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