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S.I.: ALTERNATIVE DATA COLLECTION AND ANALYSIS METHODS FOR DISASTER RECONN

A hybrid model for post-earthquake performance assessments in challenging contexts

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Abstract
Disasters provide an invaluable opportunity to evaluate contemporary design standards and construction practices; these evaluations have historically relied upon experts, which inherently limited the speed, scope and coverage of post-disaster reconnaissance. However, hybrid assessments that localize data collection and engage remote expertise offer a promising alternative, particularly in challenging contexts. This paper describes a multiphase hybrid assessment conducting rapid assessments with wide coverage followed by detailed assessments of specific building subclasses following the 2021 M7.2 earthquake in Haiti, where security issues limited international participation. The rapid assessment classified and assigned global damage ratings to over 12,500 buildings using over 40 non-expert local data collectors to feed imagery to dozens of remote engineers. A detailed assessment protocol then conducted component-level evaluations of over 200 homes employing enhanced vernacular construction, identified via machine learning from nearly 40,000 acquired images. A second mobile application guided local data collectors through a systematic forensic documentation of 30 of these homes, providing remote engineers with essential implementation details. In total, this hybrid assessment underscored that performance in the 2021 earthquake fundamentally depended upon the type and consistency of the bracing scheme. The developed assessment tools and mobile apps have been shared as a demonstration of how a hybrid approach can be used for rapid and detailed assessments following major earthquakes in challenging contexts. More importantly, the open datasets generated continue to inform efforts to promote greater use of enhanced vernacular architecture as a multi-hazard resilient typology that can deliver life-safety in low-income countries.

Keywords Haiti · Earthquake reconnaissance · Damage assessment · Housing · Vernacular architecture

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1 Introduction

Disasters provide an invaluable opportunity to validate whether adopted design philosophies are effective in achieving their stated performance objectives in the face of natural hazards. This is especially true for major earthquakes, which are comparatively rare within the natural hazards targeted by contemporary design standards. Thus a rich tradition of field reconnaissance has emerged in the efforts to systemize the collection of this invaluable data (Wartman et al. 2020). While reconnaissance technologies have rapidly advanced in recent decades to include an array of imaging and measurement platforms, automated capture and processing of remote, aerial and surface imagery, and mining of social media and citizen science data (Berman et al. 2020; Contreras et al. 2021, 2022), we focus herein on one staple in the reconnaissance field: on-site performance assessments by experts. These performance assessments traditionally involve teams of experts tasked with documenting the event's impact, either for the purposes of research or with the official function of certifying buildings' condition for re-occupancy using frameworks such as ATC-20 (ATC 2005). The former class of data collection initiatives has evolved over time both with respect to the organization of its teams as well as its standardization of data collection processes. For example, in the US, the early efforts of organizations like the Earthquake Engineering Research Institute (EERI) (EERI 1971) were eventually complemented by the establishment of the Geotechnical Extreme Events Reconnaissance (GEER) association (Bray et al. 2019). With the later arrival of the Structural Engineering Extreme Events Reconnaissance (StEER) network (Kijewski-Correa et al. 2021a), greater emphasis was placed on large-scale systematic documentation of building inventories using standardized assessments implemented in mobile applications. Beyond validating the design state-of-the-art, access to standardized and unbiased datasets of ground-level observations can also make important contributions to improving the reliability of rapid loss estimation and impact forecasting tools (Wald 2013) and typology-specific fragility descriptions (Laguerre et al. 2024).

Achieving a reliable and standardized performance assessment is generally accomplished through one of two approaches: direct assignment of global damage ratings, where skilled evaluators assign a qualitative global damage rating by subjectively interpreting the overall condition of the structure, or through component-level damage ratings, where expert assessors assign a percentage of damage to each component through what is often a more objective and systematic inventorying process. The former approach is certainly valuable in settings where an immediate rating is necessary to rapidly communicate the severity of an event geospatially and/or when field conditions limit the amount of time/pool of assessors available to cover a large affected area. While the alternate approach's parsing of damage percentages across numerous components is inherently more time consuming, component-level damage ratings provide richer information on the drivers of performance. They can also still be automatically mapped to global damage rating scales, e.g., Vickery et al. (2006), for more objective assignment of damage states when large teams of assessors with variable levels of experience are used.

Whether conducting a rapid assessment directly assigning global damage ratings or engaging in detailed assessments that inventory component-level performance, the traditional approach to gathering perishable data after major disasters relies upon a finite pool of skilled evaluators, which inherently limits the speed, scope and coverage of any post-disaster reconnaissance effort. Timing in coverage is especially critical after any major disaster, as ready access ensures perishable data on structural performance can be collected before debris is disturbed, or in the case of earthquakes, before subsequent aftershocks destroy evidence of the main shock's impacts. While it was not uncommon for international teams to embed local engineers in their reconnaissance efforts to both bolster the number of assessors and integrate local knowledge, major disasters inevitably draw international experts to the affected area, especially when local assessment capacity is limited. However, the COVID-19 pandemic challenged this traditional mode of operation, forcing organizations that led reconnaissance efforts worldwide to adapt their approaches due to travel bans, begging new questions regarding the advantages of localizing assessment efforts, and when appropriate, marrying those with remote expertise to enhance the depth and quality of assessments (Aktas and So 2022). With clear advantages in reducing risk, minimizing travel burdens, infusing local knowledge, and broadening participation in assessment efforts, promising models for hybrid assessment should not only be developed and vetted, but shared across reconnaissance organizations.

This paper responds by examining how to systemize and open-source hybrid assessments that combine local and remote capacity to conduct both subjective rapid assessments and more objective detailed assessments of buildings. The assessment approach is demonstrated for a sustained data collection and enrichment exercise conducted following the August 2021 M7.2 earthquake in Nippes, Haiti. The paper begins by contextualizing this effort within the wider landscape of efforts to crowdsource assessments following major earthquakes, before introducing the earthquake used as the illustrative case study. We then present two hybrid assessment approaches: a rapid assessment for wide geographic coverage followed by a detailed assessment that focuses on specific subclasses of buildings, leveraging machine learning techniques. For each, we present the local and remote aspects of the hybrid model, including a preview of the data and insights generated, followed by conclusions and prospects for promoting greater use of hybrid assessments in the future.

2 Use of hybrid assessments in earthquake reconnaissance

The segmentation of data collection, classification and enrichment tasks across field and remote teams is not a new concept in the study of major earthquakes. The sheer size of the 2010 Haiti earthquake, for example, was a motivator for some of the earliest hybrid assessments, using remote efforts in place of tasks traditionally executed in the field by experts. While at coarser granularity and a time when computer vision techniques were still evolving, efforts organized by ImageCat aided in the rapid assessment of satellite imagery through early crowdsourcing platforms (Bevington et al. 2015). The concept of crowdsourcing microtasks to expand the workforce available to support large-scale post-disaster assessments was promising and continued to gain traction through efforts like Crisis Mapping (Ziemke 2012). To this day, crowds continue to play a role in annotating images for the purposes of training machine learning algorithms to detect features in building images (Yu et al. 2020). These machine learning algorithms have potential to revolutionize remote sensing capabilities for assessing disaster impacts (Wagenaar et al. 2020), building on the early applications of remote sensing for damage detection in the 2010 Haiti earthquake (Corbane et al. 2011). While remote imagery has admitted limitations in understanding which components drive the observed building performance, access to surface-level imaging campaigns is now enabling even more detailed component-level assessment of building damage using computer vision over large geographic areas (Lenjani et al. 2020). While artificial intelligence is helping to accelerate these large-scale assessment capabilities, more component-level detailed assessments of failure mechanisms and their severity, which require more nuanced interpretation, often still rely on human cognition. However, even these tasks can be effectively paraskilled into a series of structured and repeatable operations crowdsourced out to non-experts, as demonstrated by other efforts after the 2010 earthquake in Haiti (Zhai et al. 2012). Through training and the introduction of well-defined assessment workflows, non-experts conducted detailed component-level assessments on par or even superior to those conducted by engineers (Staffelbach et al. 2014), in part because the tasks were structured to remove the subjectivity experts may over-rely upon when completing a familiar assessment exercise. We will therefore examine in this paper how an earthquake in Haiti, in this case in 2021, provides yet another opportunity to innovate crowdsourcing efforts for remote assessment tasks.

Beyond these classification tasks, local actors have also been effectively mobilized in the collection of data in hybrid assessments, particularly during the COVID-19 pandemic. Earthquake Engineering Field Investigation Team (EEFIT) efforts after the 30 October 2020 Aegean Sea Earthquake demonstrated that sufficiently-trained local engineers with a structured mobile application could generate reliable datasets quality-assured by a larger remote team to yield a high-quality hybrid approach (Aktas et al. 2022a, b). The public's social media posts have similarly proven valuable to the study of disaster experiences through locally-sourced data (Jamali et al. 2019). As such, social media is leveraged by a number of organizations working in virtual teams in the wake of a major earthquake to identify notable failures and map patterns of damage (Fischer and Hakhamaneshi 2019; Kijewski-Correa et al. 2021a). This shift has been made possible by rapid advances in smartphone technologies: increasingly reliable geolocation capabilities, rapidly advancing high-resolution cameras, and seamless content-sharing through a range of apps like Twitter/X. Citizen science has further demonstrated how the scientific community has taken advantage of these distributed sensing capabilities by mobilizing non-experts in the collection of reliable scientific data (Newman et al. 2012). More powerfully, these smartphones are pervasive across the world, including in low- and middle-income countries, providing the scientific community with coverage in areas that may be difficult or costly to access. We thus explore how this pervasive sensing capability can be tapped for data collection in support of both rapid and detailed assessments in challenging contexts by remotely engaging experts in new forms of hybrid assessment.

3 Case study: 2021 Nippes, Haiti earthquake

Unfortunately, the country that marshaled some of the first large-scale hybrid assessment initiatives was challenged by yet another disaster necessitating new forms of hybrid assessment. A magnitude 7.2 earthquake struck 13 km SSE of Petit Trou de Nippes in Haiti at approximately 8:29 am local time on 14 August 2021. The earthquake's epicenter of 18.408°N, 73.475°W was approximately 75 km west of the 2010 Mw 7.0 earthquake's epicenter. The 2021 earthquake affected a wide swath of Haiti's Tiburon Peninsula, notably the Departments of Nippes, Sud, and Grand'Anse, including major city centers on the north and south coasts such as Jeremie and Les Cayes, respectively, both still recovering from 2016's Hurricane Matthew (Kijewski-Correa et al. 2018), within a larger national context that was still reeling from the devastating 2010 earthquake. With now multiple compounding disasters, the recent assassination of its president, and a deteriorating economic and security environment, the research and humanitarian communities were unable to robustly field deploy in response to this disaster.

Reports of widespread damage prompted the Structural Extreme Events Reconnaissance (StEER) Network to initiate a Level 1 response, activating a Virtual Assessment Structural Team (VAST) on the day of the earthquake to begin the compilation of third party data and social media reports to inventory the damage across the three affected departments (Kijewski-Correa et al. 2021b). These early damage reports warranted an immediate escalation to a Level 2 response, which would normally instigate a rapid assessment of damage using street-level panoramic imaging collected by a Field Assessment Structural Team (FAST). However, security concerns prohibited StEER members from deploying to Haiti with these imaging platforms. The travel restrictions prompted the development of the multi-phase hybrid response described in this paper, initiating with rapid assessments that were then followed by detailed forensic assessments, both relying on local data collectors with the remote participation of engineers.

As summarized by Table 1, the data collection effort commenced in the Sud Department on 20 August 2021 with rapid assessments conducted initially under the direction of StEER. By 30 August, GeoHazards International (GHI) joined the effort to expand data collection in the Nippes Department, home of the earthquake's epicenter. Data collection efforts continued under the supervision of GHI and StEER's lead institution, the University of Notre Dame (UND), enabling an expansion of efforts in the Sud and Nippes Departments and the addition of data collectors in the Grand'Anse Department by 28 September. These expanded efforts also included the deployment of an adapted USGS Did You Feel It? survey to human subjects in the affected areas (Kijewski-Correa et al. 2022), which generated valuable data for USGS to refine its Shakemap products. All data collection for rapid assessments concluded by October 29. Remote assessments of the collected data ran in parallel with those efforts and continued into early 2022. This data was then processed to auto-classify subsets of structures for more detailed assessment in the first half of 2022. The data collection effort concluded with another round of detailed field assessments conducted for specific subclasses of buildings in January 2023, once the situation in Haiti stabilized after an extended period of unrest instigated by gas shortages and security issues.

Table 1 Sequencing of rapid and detailed assessment activities, by quarter

	2021		2022				2023
	Q3	Q4	Q1	Q2	Q3	Q4	Q1
Rapid assessment	Collect Field Data	Assess Remotely					
Detailed assessment			Auto-Classify	Assess Remotely			Collect Field Data

Note Q1, Q2, Q3, Q4 designate the quarters of each calendar year

4 Hybrid rapid assessment

With three affected departments and damage in urban, peri-urban and rural areas, speed and broad coverage were prioritized in the early stages of the reconnaissance effort. This section describes the workflow that was operationalized within days of the earthquake to conduct a light touch rapid assessment that directly assigns global damage ratings to create real-time damage maps for use by researchers and humanitarian actors. While there are a number of platforms available to customize mobile applications for data collection via smartphones, e.g., ArcGIS Survey123 and the Rapp from the NHERI RAPID Facility (Berman et al. 2020), the workflow herein describes how this effort was remotely coordinated using Fulcrum (*fulcrumapp.com*) for compatibility with the wider app suite used by the Structural Extreme Events Reconnaissance (StEER) Network and the Earthquake Engineering Research Institute (EERI). Fulcrum is a commercial platform where organizations can build user-friendly, customized mobile apps with sophisticated skip logic that can be synchronized to any smartphone. Fulcrum accesses the camera and microphone native to the smartphone so high-resolution images and audio files can be seamlessly integrated into each geolocated record. We describe herein how non-expert local data collectors used their personal smartphones with the Fulcrum app to capture perishable data that was then served to Fulcrum's web-based geospatial dashboard, where engineers could review the incoming records to remotely complete the remaining stages of the rapid assessment.

4.1 Local data collection

The design of this hybrid rapid assessment adopts a "paraskilling" approach that systematizes the routine data collection steps normally conducted by an engineer in the field: (1) geolocating the structure on OpenStreetMaps base maps, using the positioning tools available in Fulcrum and their mobile device's GPS, (2) supplying general information on the structure's location and occupancy from predefined categories, along with at-a-distance images from all sides of the building (if accessible), and (3) details of observed damage through up-close photographs contextualized by audio recordings (see Fig. 1). Field data collectors were encouraged to take pictures of any official signage or posted placards and use the embedded audio recording feature of the app to capture any details from bystanders regarding who built the building, its age, and its performance in the earthquake. This feature was particularly advantageous since we intentionally limited the number of structured fields to keep the mobile application lean, easy to learn, and fast to complete in very challenging conditions. The audio recording feature provided a quick way to still dictate any potentially valuable information that would not otherwise be captured. The customized app was built in Fulcrum, allowing it to run on any smartphone with the Fulcrum app installed (available for both iOS and Android). This essentially creates an "app within an app" that allows users to rapidly customize and distribute stable apps that are supported seamlessly by the secure, reliable wrapper afforded by the Fulcrum parent app. The authors created credentials for any organization that wished to use this app, which led to the collaboration with GHI and EEFIT described herein. The custom app presents each field with instructions/response choices in Creole and English to maximize use among Haitian and international actors. See Supplemental Material 1 a listing of all the app fields, both those populated by local data collectors

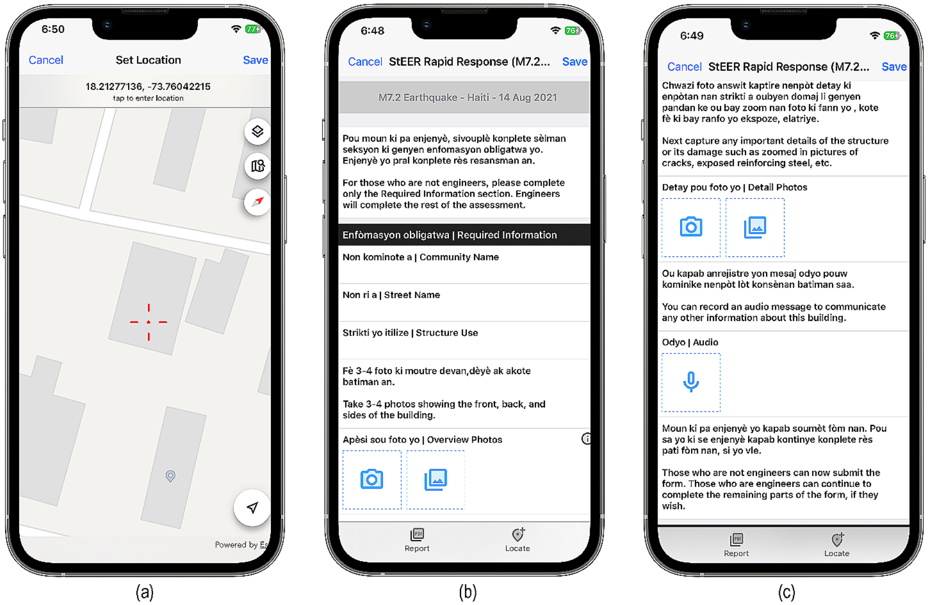
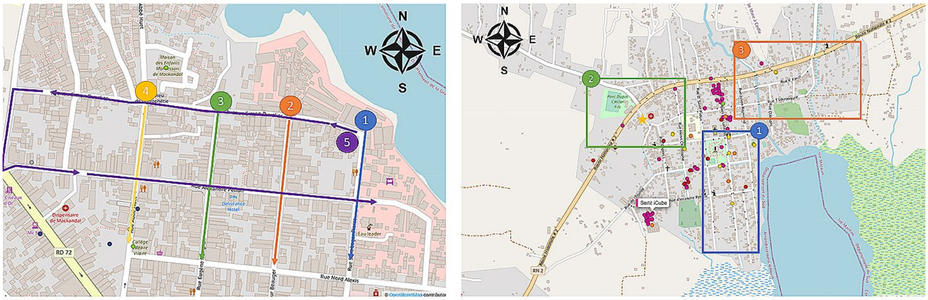


Fig. 1 Screen captures of mobile app supporting tasks paraskilled to local data collectors: (**a**) geolocation using Open Street Maps (red cross is geolocation), (**b**) supplying general information and overview photos, (**c**) capturing detailed photos of damage and audio recordings

in the field, those remotely completed by engineers, and those updated by the coordinating team/staff translator.

Records were created in the app by field data collectors who had no technical background but hailed from the departments they surveyed and were thus familiar with the communities assessed. The data collectors received basic training on use of the mobile platform, optimal device configuration, and data collection procedures. The training was conducted remotely by Zoom with bilingual guidance documents for ongoing reference. Data collectors would mobilize in teams of 2–5 persons traveling by moto(s) to an assigned geography. In order to generate an unbiased sample of building performance, field data collectors working in urban areas were assigned a new route each day; zones (polygons) were assigned to each data collector working peri-urban and rural areas. These routes and zones were communicated each morning through annotated maps (see Fig. 2), transmitted by WhatsApp. Data collectors were instructed to create a record in their mobile app for every third building encountered on their walking path with two important exceptions: assess every standard-plan home constructed by a non-governmental organization (NGO) and every critical facility (schools, hospitals/clinics, government/assembly buildings). As the Fulcrum platform will synchronize records as connectivity allows, field data collectors would see pins on their maps for every structure that had already been assessed, ensuring no duplicate records were created.

We sought to capture a representative sample of different building classes (residential, schools, commercial, government, medical/critical facilities) in each affected department. The selection of sites for data collection in each department prioritized localities based on their reported damage levels (referenced against projected ground shaking levels from USGS), building density and diversity of inventory (for greater efficiencies in data col-



(a) (b)

Fig. 2 Examples of maps communicated daily to field data collectors to define the (**a**) route or (**b**) zone each team member should sample along/within for that day. Example (**a**) is from Jeremie (urban zone) and (**b**) Aquin (peri-urban zone)

lection), and ease of access (localities along primary roads that had been cleared/repaired since the earthquake). Then as resources allowed and landslides were cleared, smaller, rural communities were added to the sample. The only deviation from this strategy was near Saint Louis du Sud, where every accessible structure within 1 km of the one known ground motion station was assessed. Unfortunately, resources and feasibility ultimately constrained the scope of the data collection efforts, particularly as the situation further deteriorated.

4.2 Remote basic assessment

Records would synchronize daily to the Fulcrum backend where the authors would execute a high-level analysis to assess completeness and readiness for expert assessment. Qualifying records would then be flagged in the Fulcrum database for a US-based staff translator, who would work directly in Fulcrum's desktop application to update the record with an English transcript of any audio files recorded in Haitian Creole. It should be noted that while Fulcrum has an application programming interface (API) and can interface with other applications to enrich records by processing data in various ways, we were not able to take advantage of this to automate the transcription process since Creole is not a commonly supported language for AI-based translation/transcription web services. With translations appended, the records could then be directed to virtual assessors, nearly 200 engineers from different universities and organizations worldwide, EEFIT being chief among them, who volunteered to remotely review each record, assign a global damage rating, and classify the structural system. Assessors were recruited through an open call and given detailed instructions with embedded videos demonstrating how to use the Fulcrum web-dashboard to access and update records. The "Assign" feature in Fulcrum was used to direct sets of records to specific assessors, who find their records pre-loaded into their dashboard when they logged into Fulcrum. There assessors could edit the assigned records, reviewing the photographic evidence and audio translation to assign three sets of fields: (1) overall damage rating with any notes justifying their assignment, (2) building description inclusive of number of stories above ground and primary structural system, and (3) a quality control code flagging the completeness of the record and the quality of their assessment (see Fig. 3). Beyond providing a reliability measure, this third set of fields allowed records that were incomplete or with poor quality images to be flagged for removal from the assessment process.

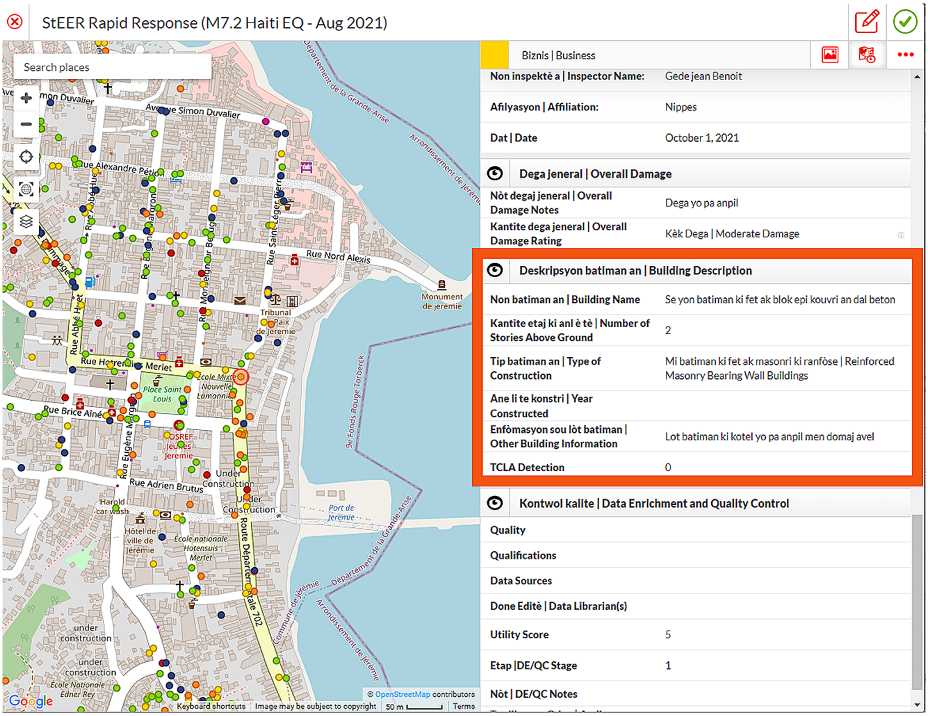


Fig. 3 Screen capture Fulcrum record editing interface showing the map view and box highlighting fields to be updated by expert assessors. Pressing the pencil logo in the upper right corner allows fields to be edited

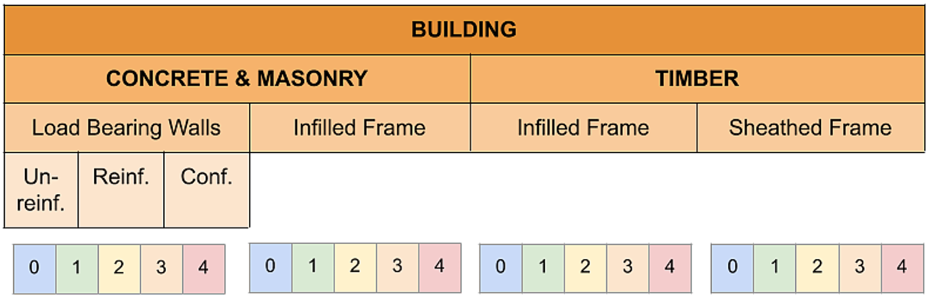


Fig. 4 Schema for classifying building typologies in Haiti, each with specific guidance for assigning damage assessment on a 5-point rating scale

To achieve a consistent and objective rating, each assessor was provided with detailed guidance on Haitian construction, which was not familiar to most volunteer assessors. We created a schema for classifying Haitian building typologies within concrete and masonry and timber subclasses (see Fig. 4). The guidance moves the assessor through a set of diagnostic questions with illustrative photos to identify the appropriate typology within these subclasses (see Supplemental Material 2). Timber systems were classified as Wood with stone infill or Wood light frame (clad with lightweight materials). Concrete and masonry classifications are more nuanced due to variable implementation practices in Haiti, e.g., masonry buildings may partition walls along their length but fail to adequately confine openings or the top of walls. Distinguishing the nuance between an infill frame, properly confined masonry or weakly confined unreinforced masonry only from images captured at a distance can be challenging, so guidance included a number of visual cues familiar to the first author based on her field work after the 2010 earthquake. These cues enabled assessors to assign the primary structural system as: Unreinforced Masonry Bearing Wall, Reinforced Masonry Bearing Wall (evidence of reinforcing steel at top of wall), Confined Masonry (presence of any confining elements), Concrete Frames with Infill Masonry (column sized thicker than infill). Any other systems would be assigned "Other".

Once the primary structural system was identified, a global damage rating could be assigned on a 5-point EMS-98-compatible scale (Grünthal 1998). Partial and total collapse were treated the same for the purposes of assessment as both violated a life safety performance objective. As the damage ratings focused on loss of vertical load-carrying capability and system-level stability, their interpretation varied for the two primary typologies (see Table 2), informed by detailed guidance and photographic examples provided to remote

Table 2 EMS-98-compatible damage ratings, interpreted for two primary typologies in Haiti

Damage rating	Description	Concrete & masonry system interpretation	Wood framed system interpretation
No damage	*No visible structural damage and either no or just slight non-structural damage*	No/slight evidence of cracking of infill/finishes	No/slight evidence of cracking of infill/finishes or dislodging of cover
Minor damage	*Slight structural damage and slight to moderate level of non-structural damage*	Surface damage (cracking of infill or stucco cover lost)	Minor loss of infill at top of wall or minor dislodging of wall cover
Moderate damage	*Moderate structural damage and moderate to severe level of non-structural damage*	Cracks in masonry walls but majority of vertical-load-carrying capacity retained	Loss of infill in select panels, minor racking of frame
Severe damage	*Severe structural damage and moderate to severe level of non-structural damage*	Significant cracks in walls or columns compromising vertical carrying capacity, but alternate load paths available	Loss of infill in multiple panels, more significant racking without loss of stability or ability to support roof
Partial/Total collapse	*Severe structural damage and moderate to severe level of non-structural damage*	Collapse of full story or part of floorplan up to total collapse	Complete or partial collapse, framing no longer able to support roof

assessors (see Supplemental Material 2, which further references a Classification Manual -- a compilation of additional examples and detailed explanations).

4.3 Proof-of-concept

This hybrid rapid assessment created records for 12,699 buildings between 20 August and 29 October 2021, which were reduced to 12,536 following quality assurance processes. Records in Fig. 5 cluster around the major population centers in the three surveyed departments. Another notable cluster of records in the Sud Department, near the town of St. Louis du Sud, documented all buildings within a fixed radius of the one ground motion station that was operational at the time of the earthquake. By adopting a lightweight rapid assessment for the first wave of data collection, teams were able to move swiftly to capture perishable data despite the challenging conditions created by obstructed roads, gas shortages and unrest. Records in Sud and Nippes departments were acquired between 20 August and 8 October 2021, and in Grand'Anse from 28 September to 29 October 2021. At its peak, the effort leveraged 40 local data collectors per day and produced an open data set that ultimately reached areas that official government-affiliated assessment teams confined to primary and secondary roads could not.

As summarized by Table 3, housing constitutes over 80% of the records collected, and as a poorly regulated building class, had the highest rates of moderate to severe damage.

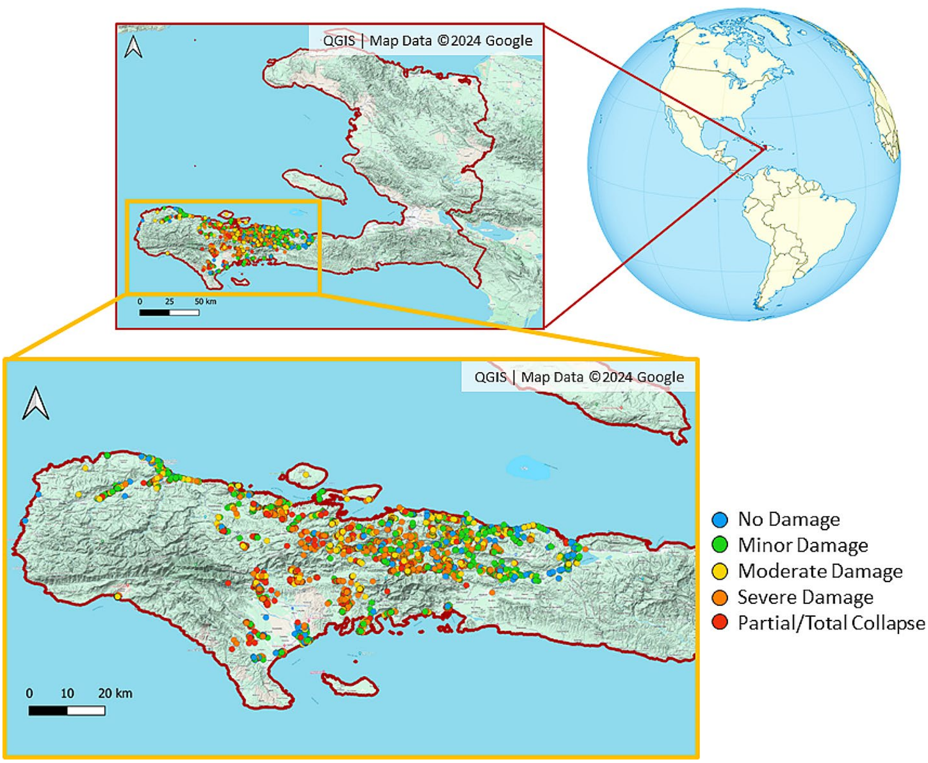


Fig. 5 Geospatial distribution of rapid assessments completed following the 2021 Haiti earthquake, color coded by assigned damage rating

Emphasis on critical facilities in the sampling strategy generated a reasonable proportion of schools and churches. While more formally constructed buildings like schools, government buildings, medical facilities and community centers performed comparatively better, churches had the highest collapse rates of any occupancy. These buildings may be historical tall stone masonry buildings with ineffective buttressing or contemporary construction that is single-story but uses weakly-confined or unreinforced masonry walls over long, open floor plans with minimal out of plane support. As discussed in Kijewski-Correa et al. (2022), a third of the building inventory was characterized as vernacular timber and masonry typologies traditionally used in Haitian housing, including *kay mur* (light timber frame, thin fieldstone masonry infill), *kay mélange* (like kay mur but with backing boards), and *kay klisé* (a type of wattle & daub) (Cuny 1982). As this vernacular construction showed evidence of superior performance in comparison with various masonry typologies and is a cost-effective and locally-sustainable construction technique, it became the focus of the subsequent detailed assessment.

5 Hybrid detailed assessment

The open dataset created under this hybrid rapid assessment effort enabled a range of remote investigations, including a collaborative effort with EEFIT (Whitworth et al. 2022). The dataset also spurred interest in the study of vernacular architecture (Dönmez and Aktaş 2023), and particularly means to enhance the seismic performance of these homes using Techniques Constructives Locales Améliorées (TCLA) promoted by NGOs in rural areas. TCLA homes were built after 2016's Hurricane Matthew in many of the same communes that experienced strong shaking in the 2021 earthquake, thus providing an opportunity to field-validate this typology's multi-hazard performance. TCLAs rely upon braced wooden posts for their primary framing, infilled with a mixture of small stones and binding materials such as lime or cement (Dejeant et al. 2014). Optional backing boards further stiffen the wall systems; in the absence of backing boards, wire mesh is sometimes provided to prevent injuries instigated by the out-of-plane collapse of fill material. These houses are comparatively lightweight, topped with wood-framed corrugated galvanized iron (CGI) sheet roofs.

The question then became, how could TCLAs documented in the first wave of basic assessments be used to assess the performance of this residential subclass? This question prompted the creation of a detailed assessment to further enrich existing records of TCLA

Table 3 Summary of building performance in 2021 Haiti Earthquake, by occupancy

	N	% Total	Part/Full collapse	Severe damage	Moderate damage	Minor damage	No visible damage
Residential	10,157	81.0%	14.3%	29.0%	23.3%	23.6%	9.9%
School	927	7.4%	6.5%	11.6%	18.6%	39.5%	23.9%
Church	723	5.8%	21.2%	17.8%	17.7%	28.6%	14.7%
Commercial	421	3.4%	10.3%	17.7%	19.7%	27.4%	25.1%
Government	125	1.0%	4.6%	16.5%	18.3%	28.4%	32.1%
Medical	102	0.8%	7.1%	6.1%	17.3%	35.7%	33.7%
Community	46	0.4%	9.1%	12.1%	30.3%	42.4%	6.1%
Other	35	0.3%	19.1%	29.8%	14.9%	21.3%	14.9%
Total	12,536	100%	13.9%	26.4%	22.4%	25.3%	12.0%

houses with more objective, component-level damage ratings. Insights from the analysis of these more detailed remote assessments ultimately guided the creation of a follow-up forensic data collection protocol that was programmed into Fulcrum for execution by local data collectors. However, these detailed assessments could not commence until the TCLA homes were identified among the over twelve thousand records collected after the earthquake. This multi-stage hybrid detailed assessment is described herein, as well as the use of machine learning techniques to streamline the identification of the TCLA homes.

5.1 Automated classification

Unfortunately, TCLA was not included as a specific subclass with the initial schema developed for structural system classification by remote assessors. The nearest class, Wood with Stone Infill, would encompass traditional timber housing as well as TCLAs. Thus we developed a binary classification model trained to automatically detect the presence of TCLA bracing elements in the photographs within the rapid assessment database. The model leveraged transfer learning via the MobileNetV2 convolutional neural network (CNN) object detection architecture (Sandler et al. 2019), retrieved from the Tensorflow 2 Detection Model Zoo (Abadi et al. 2015). Initial weights were set to model weights pre-trained for the task of object detection on the 2017 COCO Detection set to decrease the computational resources required for training (Lin et al. 2015). The model was trained ($N=108$) and tested ($N=20$) on manually-labeled images scraped from various NGO publications archived in the United Nations (UN) Shelter Cluster. The number of images available for training and testing was constrained by the limited reporting on TCLAs in the public domain. For this task, peak performance was achieved by using an Adam optimizer with a hyperparameter factor of 0.9 and a batch size of 4. The optimizer started with a large initial learning rate, 0.08, reduced by applying a cosine decay function to the optimizer step until a local minimum was achieved. A warm-up learning rate of 0.0267 was set to combat early overfitting and is slowly increased to the initial value after 1000 training steps. The model was trained for 20,000 steps, with localization, classification and regularization losses evaluated every 100 training steps using a cross entropy loss function.

Brace detections are denoted by a bounding box and are evaluated by their level of confidence (see Fig. 6). As the goal was to maximize the number of TCLAs retained for detailed analysis by humans, we opted to relax the confidence threshold (set at 50%) and created a post-processor to flag a record as "possible TCLA" whenever one or more unique bracing elements were detected in that image at a minimum of 50% confidence. A separate database of 61 images collected in Haiti after the 2021 earthquake as part of the USGS for Did You Feel It benchmarking (Kijewski-Correa et al. 2022) were manually labeled and used as a validation set. Manual labeling considered both NGO-constructed TCLA homes as well as local replications of TCLAs by households. The TCLA classifier achieved an accuracy of 66%, with 34% of ground truth positive images falsely classified as non-TCLA, owing in part to the generous confidence threshold adopted.

False negatives were often due to the lack of color contrast between the stone infill material and the wooden bracing elements, as structures with distinct color gradients were successfully classified. Additionally, surface imagery captured by field data collectors in the Fulcrum database were not always level, resulting in a rotation of the brace plane or photos captured at an isometric angle, which often resulted in false negatives. These detection fail-

(a) (b)

Fig. 6 Examples of bounding box detection with prediction confidence on two TCLA homes; home on the left is unfinished with braces clearly visible but braces can even be detected on the stuccoed home on the right

ures can be explained by the fact that the training set was derived from professional-grade photos of finished houses captured with level cameras positioned orthogonal to the front face of the building. Notably, most NGOs use paint to treat their wood posts and beams, adopting a fairly consistent painting scheme with a high color gradient between the paint on the wood posts and braces and the paint used for the infill. This training data was thus less likely to detect low-contrast TCLAs like those in Fig. 6. To ensure the model was robust to in-the-wild images taken at various angles and unpainted TCLAs, it was retrained for 20,000 additional steps with the 61 labeled images used in the prior validation. These photos were taken by the same field data collectors and were more representative of the diversity of image quality in the larger rapid assessment database. The refined model achieved an accuracy of 87% when adopting a minimum confidence threshold of 50%, with a false positive rate of 5.5%.

The retrained TCLA classifier was then used to process the entire collection of images in the full rapid assessment database. To decrease computational burden, detail photos were omitted from the analysis as they typically did not display distinct bracing features. In total, 39,781 overview photos were parsed by the brace object detection model on a local desktop PC with a 3.60 GHz processor and 160 GB of RAM. The detection sequence completed in approximately 17 h, identifying 4,988 photos as possible TCLAs. The authors conducted a first pass on the identified images to select the subset that would be retained for detailed assessment based on image quality and the features visible in the image. Only 715 images were ultimately retained and a post-processing script concatenated individual images with their respective Fulcrum record to generate a database of 252 geotagged records suitable for a remote detailed assessment.

5.2 Remote detailed assessment

To determine how various features of TCLAs correlated with their observed performance in the 2021 earthquake, each of the 252 records would need a detailed assessment that inventoried features and damage at the component level. In the absence of any standardized assessment procedure for this class of structure, we developed an ex-post detailed assessment

Table 4 Overview of remote detailed assessment conducted ex-post for TCLA homes

General building information & geometry	
General building information	Meta-data, location, occupancy, structural system, year of construction, implementing NGO
Media	Audio and translation, overview and detail photos
Geometry	Number of stories, plan dimensions and geometry
Soil and foundation system	
Foundation	Foundation type, height, connections
Superstructure: wall systems	
Vertical posts	Wood type, treatment, deterioration
Panel segmentation	Panel geometry and spacing
Infill	Bracing details, infill material, backing board details
Superstructure: roof systems	
Roof to wall connection	Connection type and number of connections
Roof	Roof shape, cover and extensions
Damage rating	
Global damage rating	5-pt global damage rating
Component damage rating	Qualitative ratings (ground failure, foundation, foundation to wall connections, vertical posts, walls)
Recommended action	Follow-up rating

procedure for TCLAs that would enable engineers to remotely conduct a component-level assessment of each TCLA home based on the photos collected during the rapid assessment. The protocol systematically inventoried component subclasses to assign materials, configurations, and implementation details to each record. The protocol fields and response choices were developed based on a review of the standard designs implemented by various NGOs following Hurricane Matthew and included in the UN Shelter Cluster's current Shelter Toolkit.[1] Note that while this protocol was specific to TCLA housing in Haiti, it could be readily generalized to assess other forms of vernacular architecture elsewhere. The protocol resulted in the assignment of 34 additional fields to each TCLA record (see Table 4 for summary and Supplementary Material 3 for the full listing of fields and response choices). The assessment was directly conducted in a cloud-based database with multiple choice fields encoded as drop down menus, so that multiple engineers could work simultaneously in the database to assess the records.

In the *General Building Information & Geometry* stage, remote assessors would assign the TCLA to a possible implementing organization based on visual markers unique to their design or specifics in the audio translation[2]; a script also calculated the epicentral distance based on the home's latitude and longitude. Any geometric characteristics such as plan geometry (square, rectangular, L-shaped), plan dimensions, and number of rooms are assigned, if discernable or inferable from the plans of the implementing NGO. The assessment then moves along the load path from foundation to roof. The *Soil and Foundation*

[1] https://sheltercluster.org/toolkit/gsc-coordination-toolkit.

[2] Only 51 of the 252 TCLA homes could be traced back to an implementing NGO.

System stage queries details such as foundation type and height above grade as well as any visible connection details. The *Superstructure: Wall Systems* stage notes the type, treatment and condition of wood posts, bracing configurations, and framing details, as well as infill characteristics. The *Superstructure: Roof Systems* stage finally examines roof geometry and cover, as well as any visible connection details. The *Damage Rating* stage assigns a corresponding qualitative damage rating to each component along the load path based on specifics of observed damage mechanisms and extent, yielding a higher-fidelity description of damage that is more objective than the global ratings assigned in the rapid assessment. To facilitate subsequent analysis, each qualitative damage assessment was encoded on the backend to an equivalent 0–3 scale, where 0 is undamaged and 3 represents the complete failure of that component. Assessors then use the *Recommended Action* field to flag any record worthy of follow-up field visits as a representative case study.

5.3 Forensic data collection

The process of conducting this remote detailed assessment of TCLAs underscored the value of returning to the field for more in-depth documentation of records flagged for follow-up to document specifics of connection details or presence of backing boards. Unfortunately, security conditions continued to limit the ability to send engineering teams in to conduct up-close forensic assessments even a year after the earthquake. In response, we developed another Creole-language mobile application in Fulcrum to systematize detailed data collection for forensic evaluation of TCLA homes. The field protocol developed for the app documents both the interior and exterior of the home and inventories the full load path on all four sides of the building. To facilitate remote analysis by engineers, conventions were established for sequencing photo documentation (the front of the home was defined as wall 1, with walls numbered sequentially working counter-clockwise from this point). A range of screening and gateway questions were incorporated to help local data collectors bypass question sequences that would not be applicable to a given situation.

The assessment in Table 5 had four major steps, with a number of subtasks accompanied by one or more prescribed photos. In total, the app collected up to 341 pieces of data along the load path from the foundation to the roof for each of the home's four exterior walls. See the full field protocol in English and Creole for specifics (Kijewski-Correa 2023). Step 1 asked homeowners a number of questions about the home's performance as well as the implementing organization, any modifications or repairs since the earthquake, and the home's functionality level following the earthquake. Step 2 defined the floorplan geometry and dimensions with specifics of the foundation system. Step 3 focused on exterior data collection for each of the four walls, beginning with wall 1. Skip logic allowed assessors to bypass submenus if a wall was inaccessible. For each wall, the field data collector would work from the soil to the top of each wall taking overview and detail photos, recording orientations, dimensions, spacing and quantities of components such as posts and braces. If possible, the assessor would classify connections and fill/mortar types, as well as noting wood species and any treatment used. Evidence of damage or deterioration (insects, weathering) in any component was distinguished, when possible, and photo documented. The roof cover, attachments and any visible damage were also recorded as part of Step 3. Step 4 initiated the interior assessment, which was enabled only if the assessor indicated that the structure was safe to enter and owner permission was granted. The interior assessment

Table 5 Forensic data collection app structure

Step 1: Building & Owner Information			
Step 2: Floorplan and Foundation Details			
Step 3: Exterior Assessment			
Step 3a: Wall 1	**Step 3b: Wall 2**	**Step 3c: Wall 3**	**Step 3d: Wall 4**
Site conditions	Site Conditions	Site Conditions	Site Conditions
Wall dimensions	Wall Dimensions	Wall Dimensions	Wall Dimensions
Foundation	Foundation	Foundation	Foundation
Foundation-to-wall connection	Foundation-to-Wall Connection	Foundation-to-Wall Connection	Foundation-to-Wall Connection
Wall configuration (posts, infill, braces)	Wall Configuration (Posts, Infill, Braces)	Wall Configuration (Posts, Infill, Braces)	Wall Configuration (Posts, Infill, Braces)
Step 3e: Roof cover & geometry			
Step 4: Interior assessment			
Step 4a: Interior configuration and roof system			
Step 4b: wall 1	**Step 4c: Wall 2**	**Step 4d: Wall 3**	**Step 4e: Wall 4**
Backing boards	Backing Boards	Backing Boards	Backing Boards
Roof-to-wall connection	Roof-to-Wall Connection	Roof-to-Wall Connection	Roof-to-Wall Connection
Foundation-to-wall connection	Foundation-to-Wall Connection	Foundation-to-Wall Connection	Foundation-to-Wall Connection

established the floorplan layout, interior partitioning and roof framing, before conducting a wall-by-wall assessment, beginning with wall 1. The wall assessments documented any backing boards and their condition, roof-to-wall and foundation-to-wall connections, as well as any observable damage.

Thirty well-performing TCLA houses in regions of strong shaking were documented in January 2023 using this app, including NGO-constructed homes southeast of Corail in Grand'Anse (44 km from the epicenter) and Tirouelle in Nippes (18 km from the epicenter), with assessment time ranging from 45 to 90 min. The records were then interrogated in detail by the authors to develop case studies on the implementation and adaptation of TCLA standard designs in Haiti. Of these 30 TCLA homes, 21 sustained damage in the earthquake. Among those 21, only five had been repaired, with another undergoing repair, at the time of the assessment. While these damages were largely confined to the infill and the structures were tarped and habitable, repair actions were delayed as part of the protracted recovery processes observed in past disasters in Haiti (Kijewski-Correa et al. 2019).

5.4 Proof-of-concept

The detailed assessment database formed the basis of subsequent analyses to determine the components that correlated most significantly with the observed damage levels, with the case studies from the forensic data collection providing specifics of how these components were implemented in well-performing homes. The vast majority (~87%) of TCLA homes in the detailed assessment database did not sustain severe damage or collapse in the earthquake, likely due to their lightweight, single-story construction. Evidence of ground failure was observed in only 14% of the homes. Damage to the foundation was rarely observed

(~5%) and was largely confined to minor cracking or crumbling/spalling. Instead, damage concentrated in the wall infill material, with 28.6% of houses experiencing severe infill cracking to severe loss of the infill and/or braces. While only 13% of TCLAs had undamaged walls, the majority sustained only minor cracking or loss of infill material (see Fig. 7), suggesting that the failures were well contained due to the segmentation of the wall panels by posts and braces. Minor infill cracking and loss may be unavoidable independent of improving the capacity of available infill materials or further reduction in the overall displacement demand on these brittle infill panels. Notably, even when infill wall panels were significantly damaged, the structures still maintained life safety objectives due to the ability of posts to maintain the vertical load path supporting their lightweight roofs.

Unsupervised machine learning was used to investigate multidimensional trends in the detailed assessment database in an effort to isolate the combination of building features that drove TCLA performance in the 2021 earthquake. Specifically, a k-means clustering algorithm was employed to find homogeneous groups of data points within this dataset, using the Euclidean distance to minimize the distance between individual points and their respective cluster centers (Madhulatha 2012). One-hot encoding was employed to encode these categorical features into a one of K-scheme. The elbow method is then used to determine the optimal number of clusters for the analysis by plotting model inertia, also known as the within cluster sum of squares (WCSS), calculated as the sum of squared Euclidean distances between points and their respective cluster centers, against the number of clusters, K. The inflection point or the "elbow" of the curve indicates the best fit K for the underlying data: the optimal number of clusters for this analysis was K = 20.

Fig. 7 Example of TCLA with minor infill loss (Fulcrum ID: a39ea13e-050c-45bb-a557-7d4e6115c9e2)

A k-means algorithm is employed with this optimal K = 20 clusters, using a cluster-based feature weighting technique to investigate the importance of each variable in a cluster based on the direct analysis of a cluster centroid's position. Feature weights are extracted by calculating the maximum centroid dimensional movement when the location of a given feature is considered against the location of the cluster center. Based on the Euclidean distance, dominant features will have the highest impact on WCSS minimization (Alghofaili 2021). This procedure yielded five notable clusters based on minimization of WCSS and influence on cluster location; unsurprisingly these clusters were associated with the global damage rating. Features within these clusters with a high positive weight indicate that their existence or large magnitude had a significant impact on the cluster location. Conversely, features with high negative weights indicate that their non-existence or low magnitude had a significant impact on classification. When a positive feature has a corresponding negative feature, it can thus be concluded that this feature class is a major driver of that cluster, in this case of the performance of homes with that damage level. These opposing pairs are summarized for each overall damage rating (cluster) in Table 6, with the exception of the partial/total collapse cluster which had too small of a population ($N = 4$) to meaningfully analyze, a testament in and of itself to the performance of TCLA homes in the 2021 earthquake.

These findings suggest that TCLA homes with no to minor damage are characterized by a continuous concrete beam on mixed masonry foundation and employ X-bracing on all wall panels. Damage increases when homes are inconsistent in the use of bracing and when foundations are significantly elevated or employ stone masonry platform foundations. Frequent flooding in Haiti from tropical storms and seasonal rains drives the practice of elevating foundations higher than NGO-standard plans may prescribe, with stone masonry being the most cost effective way to achieve that elevation, but also highly vulnerable due to dry stacking or poor masonry work. This highlights the multi-hazard trade-offs that must be addressed in guidance issued for these housing designs. Notably, the absence of "epicentral distance" from Table 6 indicates that it did not have substantive influence on the observed performance, suggesting that TCLA homes performed well in the near-field region. More importantly, of the many features emphasized in the construction of these homes, e.g., limiting the size of stone used in infill, the superstructure's observed performance in the 2021 earthquake fundamentally depended upon the type and consistency of the bracing scheme, supporting the findings of past experimental studies (Vieux-Champagne et al. 2014). Such insights can help builder training programs to better focus their messaging on these key drivers of seismic resistance and foreground these in quality control practices.

6 Conclusions

Disasters provide an invaluable opportunity to evaluate the effectiveness of contemporary design standards, inspiring a rich tradition of field reconnaissance to collect perishable data on built environment performance. However, the efforts to systematically collect and interpret this data has historically relied upon a finite pool of skilled evaluators, which inherently limits the speed, scope and coverage of any post-disaster reconnaissance effort. Localizing assessment efforts can overcome these challenges, and when appropriately coupled with remote expertise, can facilitate hybrid assessments that deliver the same quality and possibly larger volumes of data, while reducing risk, minimizing travel burdens, infusing local

Table 6 Feature pairs within the five clusters (global damage rating) driving TCLA performance (with feature weights)

Feature pair	Positive features	Weights	Negative features	Weights
No visible damage cluster (N=13)				
Foundation type	Continuous concrete beam on mixed masonry	0.589	Stone masonry platform	-0.645
Bracing scheme	Bracing on all panels	0.522	Bracing on most panels	-0.541
Minor damage cluster (N=34)				
Foundation type	Continuous concrete beam on mixed masonry	0.967	Concrete platform foundation	-0.535
Bracing scheme	Bracing on all panels	0.925	Bracing on some, most panels	-0.589, -0.470
Brace type	'X' brace scheme	0.596	Mixed scheme bracing	-0.535
Moderate damage cluster (N=17)				
Bracing scheme	Bracing on some panels	0.889	Bracing on all panels	-0.781
Foundation height	Significantly elevated foundation (0.5 m or more)	0.592	Slightly elevated foundation (less than 0.5 m)	-0.492
Severe damage cluster (N=19)				
Bracing scheme	Bracing on some, most panels	0.613, 0.465	Bracing on all panels	-1.016
Foundation type	Stone masonry platform	0.395	Continuous concrete beam on mixed masonry	-0.528

knowledge, and broadening participation in assessment efforts after major disasters. This paper described how the response to the August 2021 M7.2 earthquake in Nippes, Haiti developed such hybrid assessments to conduct both a rapid assessment with wide geographic coverage and detailed assessments that focus on specific subclasses of buildings when confronted with a security situation that limited international participation in reconnaissance efforts. The rapid assessment classified and assigned global damage ratings to over 12,500 buildings through the use of a mobile application deployed using the Fulcrum mobile app environment on the smartphones of over 40 non-expert local data collectors, feeding imagery to over 200 engineers working remotely to complete a basic assessment of building performance. This dataset, which reached areas that were not accessed in government-sanctioned assessment efforts, documented relatively higher rates of moderate to severe damage in the informally-constructed housing inventory. While more formally constructed buildings like critical facilities performed comparatively better, the highest rate of collapse was observed in churches. Notably, the rapid assessments suggested that vernacular construction could outperform various masonry typologies.

A detailed assessment protocol was then developed to study the drivers of the superior performance in one class of enhanced vernacular construction called Techniques Constructives Locales Améliorées (TCLA). TCLA homes were identified within the database over 12,500 buildings using a machine learning technique to detect bracing in the collected photographs. The detailed assessment protocol was then exercised by engineers working remotely to assign component-level descriptions and damage assessments to over 200 TCLA homes using photos gathered during the rapid assessment. The resulting detailed assessment database affirmed that the vast majority (~87%) of TCLA homes did not sustain severe damage or collapse in the earthquake, even in the nearfield region. Observed damage concentrated in the wall infill material and was fairly well-contained. As a result, damaged structures were able to maintain their vertical load path and were easily repaired with local and even recycled materials while occupied. Cluster analyses further confirmed that across the components inventoried by the detailed assessment, the combination of inconsistent bracing practices and significantly-elevated foundations, particularly stone masonry platforms, drove the observed damage.

The findings motivated the development of a second mobile application that could guide local data collectors through a systematic forensic documentation of the load path, providing remote engineers with essential implementation details used in 30 well-performing TCLA homes in the nearfield region. In total, this hybrid detailed assessment underscored that the superstructure's observed performance in the 2021 earthquake fundamentally depended upon the type and consistency of the bracing scheme adopted, rather than the many other features initially emphasized in training programs for TCLA homes, e.g., limiting the size of stone used for infill. Such insights can help builder training programs to better focus their messaging and quality control practices on this key driver of seismic resistance.

The various assessment protocols and mobile apps discussed in this paper have been shared with the research and humanitarian response communities as a demonstration of how a hybrid approach can be used for rapid and detailed assessments following major earthquakes in challenging contexts. More importantly, the open datasets generated by these hybrid assessment efforts have been used to improve the reliability of rapid loss estimation and impact forecasting tools and continue to inform recovery efforts following the 2021 Nippes, Haiti earthquake, particularly with respect to promoting greater use of enhanced vernacular architecture as typology that can deliver life safety under multiple hazards and can be occupied while undergoing repairs using locally available materials and skillsets.

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Author contributions Kijewski-Correa conceived and designed the study. Kijewski-Correa and Presuma developed and executed the local data collection protocol, while Mbabazi and Lochhead coordinated the remote basic assessments. Mbabazi, Lochhead and Canales conducted the remote detailed assessments, while Lochhead, Canales and Presuma developed and implemented the forensic data collection protocol. Mbabazi and Canales analyzed the data offered as proof-of-concept, while Hamburger developed and executed all machine learning techniques used in this study. Mbabazi was responsible for the quality assurance and curation of the final dataset. The first draft of the manuscript was written by Kijewski-Correa. All authors read and approved the final manuscript.

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Data availability The datasets collected under this Hybrid Model are available at https://www.designsafe-ci.org/ under project PRJ-3269 and available under the StEER account at FulcrumApp.com. Please contact the corresponding author to receive access credentials to the Fulcrum platform.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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