Reported by ACI Committee 133, Disaster Reconnaissance

The Institute's Team for Damage Investigations

Lessons learned from field deployments

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ACI Committee 133, Disaster Reconnaissance, was conceived in the aftermath of the 2010 Chilean Earthquake, an event that affected thousands of structures. That event caused extensive damage to an estimated 50 to 100 mid-rise and high-rise reinforced concrete (RC) buildings, including seven that were damaged beyond repair.[1-3] Although ACI has had a strong history of publishing assessments of disasters (refer to textbox: Historical Disasters Examined in ACI Publications), the Institute had no formal mechanism in place to deploy a team to investigate and report on critical lessons to its technical committees and membership. Furthermore, the broadening international reach of the ACI 318 Building Code, which has been adopted or referenced in the national code of more than 30 countries, including Chile,[4] highlighted the need for ACI liaisons to be on the ground immediately after a disaster to serve as a technical resource to local engineers. Recognizing these needs, former ACI Committee 318 Chair Jack Moehle consulted with former ACI Presidents José Izquierdo-Encarnación and Luis García about the formation of a committee with a disaster reconnaissance directive. In October 2012, a proposal was submitted to the ACI Board of Direction to establish and fund a new committee with the primary objectives of:

- Providing a mechanism for evaluating the application of ACI documents internationally; and
- Disseminating deployment findings to ACI technical committees and through ACI publications.[5]

To date, the Chairs of the resulting committee, ACI Committee 133, have included Jack Moehle, Ken Elwood, Michael Kreger, and Santiago Pujol. This committee has actively engaged a diverse group of practitioners and researchers.

Historical Disasters in ACI Publications

Engineers have gathered data about building performance after natural disasters since at least the 1920s,[6,7] with some data available online from disasters as early as the 1931 Managua Earthquake.[8] One of the oldest formal programs for post-disaster reconnaissance is the Earthquake Engineering Research Institute's (EERI) Learning from Earthquakes (LFE) program, which was established in 1973.[9] Since its creation, EERI LFE has collected data after more than 300 earthquakes, and it has shared its findings in reports, in *Earthquake Spectra* articles, and in a centralized data repository.[10] While ACI has had no formal reconnaissance committee until recently, structural engineers have long disseminated the findings from their field reconnaissance studies of RC structures through ACI's periodicals.

Fig. 1: Historical disasters reported in ACI publications *(map data credits: Google, INEGI Imagery, NASA, TerraMetrics[11])*

Figure 1 presents the locations and dates of 21 earthquakes, 10 structural collapses, and two hurricanes for which reconnaissance findings were published in the *ACI Structural Journal*, *Concrete International* magazine, and ACI Special Publications. Examples of important lessons include:

- 1961—Based on observations following earthquakes in Mexico (1956, 1957, and 1959), Japan (1923 and 1948), and Chile (1960), De Cossio and Rosenblueth[12] stressed the importance of adequate anchorage of reinforcement in beam-column joints and closely spaced ties and stirrups to prevent buckling of longitudinal reinforcement;
- 1981—Yanev[13] reported that much of the low-rise RC building damage observed in the 1978 M7.8 Miyagi-Ken-Oki Earthquake in Japan occurred in buildings with torsional irregularities in their lateral force-resisting systems;
- 1982—Lew et al.[14] indicated that the collapse of a five-story condominium building in Florida was likely caused by insufficient punching shear capacity in several of the structure's slabs;
- 1989—Based on observations from the 1988 Armenian Earthquake, Wyllie[15] reiterated the importance of properly considering the connectivity of the elements in a building's structural system to achieve the intended load path; and
- 1997—Hassan and Sozen[16] described unitless indices that can be used to assess the vulnerability of buildings to seismic damage, tested using a group of buildings that suffered various levels of damage during the 1992 Erzincan, Turkey, Earthquake.

ACI Reconnaissance Activities

The decision to deploy an ACI reconnaissance team is based on several factors, including:

- Initial reports of structural damage;
- Potential for impacts to ACI standards as well as construction and engineering communities;
- Site/regional accessibility and safety; and
- Coordination with other agencies and universities.

Figure 2 shows 14 events that ACI Committee 133 has considered for deployment, including eight earthquakes, a structural fire, a wildfire, a dam failure, a tornado, a building collapse, and a bridge collapse. To date, an ACI team has been deployed to investigate six earthquakes, one bridge collapse, and one wildfire. Descriptions of these deployments, including references to reconnaissance reports and collected data, are provided in the following text. A summary of data links and counts of structures surveyed is provided in Table 1. For earthquakes, teams have collected building coordinates and addresses, approximate floor plan sketches, dimensions of structural and nonstructural elements, and photographs and notes on location and severity of damage to these elements. In some cases, teams have also been provided formal architectural layouts, structural drawings, and structural analysis models. Also, teams have collected data for structures with various levels of damage rather than for only the most heavily damaged structures. For disasters other than earthquakes, a standardized data collection process has not yet been established; accordingly, data collection plans are made prior to each deployment.

Table 1:
Summary of ACI Committee 133 deployments

Event	Data links	Structures
2015 Nepal Earthquakes	www.datacenterhub.org/resources/238	146 low-rise buildings
	www.datacenterhub.org/resources/242	30 high-rise buildings
2016 Taiwan Earthquake	www.datacenterhub.org/resources/14098	130 buildings
2016 Ecuador Earthquake	www.datacenterhub.org/resources/14160	173 buildings
2017 Mexico Earthquake	www.datacenterhub.org/resources/14746	125 buildings
2017 Pohang Earthquake	www.datacenterhub.org/resources/14728	75 buildings
2018 Chirajara Bridge collapse	N/A	1 bridge
2018 Camp Fire	N/A	36 buildings
2019 Albania Earthquake	N/A	55 buildings
Total = 770 buildings + 1 bridge		

2015 Nepal Earthquakes

Two major earthquakes occurred in Nepal in 2015: a moment magnitude (M_w) 7.8 on April 25, and a M_w 7.3 on May 12. These earthquakes were followed by more than 400 aftershocks with magnitudes larger than 4.0. About 500,000 buildings were destroyed and over 250,000 buildings were damaged during the earthquakes and their aftershocks.[17] In

Fig. 2: Events evaluated for ACI Committee 133 deployment. Green markers indicate that an ACI reconnaissance team was deployed. Purple markers indicate that no team was deployed *(map data credits: Google, INEGI Imagery, NASA, TerraMetrics[11])*

mid-June 2015, ACI Committee 133 deployed a team to survey RC buildings in Nepal's capital, Kathmandu. Together with 17 volunteer civil engineers from local government and private industry, the team surveyed and collected data for low-rise and high-rise RC buildings. In general, low-rise buildings (less than eight stories) had nonengineered structural frames and clay brick masonry partition walls, while high-rise buildings (eight or more stories) had engineered structural frames and clay brick masonry partition walls. Figure 3 shows severe damage to unreinforced masonry infill in low-rise and high-rise buildings.[18,19] Collapse of the first story in the low-rise building (left) demonstrates the soft-story vulnerability. More information about the reconnaissance can be found in Shah et al.[20]

2016 Taiwan Earthquake

On February 6, 2016, the M_w 7.8 Meinong Earthquake occurred in Kaohsiung City in southern Taiwan. Much damage was observed in Tainan City, approximately 40 km (25 miles) from the epicenter. Reports suggested that most fatalities resulted from the collapse of a 14-story residential building. ACI Committee 133 deployed a team in March 2016, supported in part by the National Science Foundation (NSF), to join researchers from the Taiwanese National Center for Research on Earthquake Engineering (NCREE) to investigate the effects of the earthquake on RC structures. Over 12 days, 119 low-rise school, residential, and government buildings and 11 structures between eight and 23 stories tall were surveyed around Tainan City. In addition to conventional techniques, teams used aerial drones to collect videos of structures. Members of the ACI team investigated the failure of a corner column in a 14-story building in Tainan City, and they concluded that the failure was the result of axial demands imposed from discontinuous RC walls intended to function as partitions.[21] The team also conducted an evaluation of four different seismic vulnerability screening indices, including that proposed by Hassan and Sozen[16] and another then used in Taiwan. Figure 4 shows damage that was observed in columns in two different buildings.[22]

Fig. 3: Buildings damaged in the 2015 Nepal Earthquake: (a) low-rise building *(after Reference 18, licensed under CC BY-SA 3.0)*; and (b) high-rise building *(after Reference 19, licensed under CC BY-SA 3.0)*

Fig. 4: Damage to columns in the 2016 Taiwan Earthquake: (a) axial compression failure; and (b) shear failure *(after Reference 22, licensed under CC BY-NC-SA 4.0)*

2016 Ecuador Earthquake

On April 16, 2016, a M_w 7.8 earthquake shook coastal Ecuador, causing severe damage to and collapse of structures, particularly around the coastal province of Manabí. Thousands of aftershocks were reported in the following months. In July 2016, ACI Committee 133 deployed a team that, together with faculty and students from Escuela Superior Politécnica del Litoral (ESPOL), surveyed RC buildings over a period of 8 days. The buildings ranged from one to six stories in height. Most of the buildings had masonry infill walls. Figure 5 shows examples of damage observed in RC frame buildings.[23]

The team focused on collecting data to evaluate Hassan Wall Index and Column Index, measures of first-story wall and column areas normalized by total floor area that were observed to be good proxies for likelihood of damage in past investigations.[16] Measurements by the team supported the usefulness of these indices, with smaller frequencies of damage for values with large wall and column indices. Noting the large quantity of buildings with captive columns, the team also measured window heights adjacent to columns and floor-to-floor heights to see how the ratio of these two heights affected vulnerability to damage. They observed that, as the ratio of window height to floor height increased beyond 20%, there was a decrease in frequency of severe damage. More information about the reconnaissance and these findings is available in Villalobos et al.[24]

Fig. 5: Damage caused in two buildings by the 2016 Ecuador Earthquake: (a) shear failures in masonry infill walls; and (b) shear failure in a short, ground-level column above infill walls ***(after Reference 23, licensed under CC BY-SA 3.0)***

Fig. 6: A typical residential building affected by the 2017 Puebla Earthquake: (a) edge frames oriented perpendicular to the street had continuous infill walls and exhibited no significant damage; and (b) edge frames oriented parallel to the street had infill walls and fenestration and exhibited shear failure in first-story columns ***(after Reference 26, licensed under CC BY-NC-SA 4.0)***

2017 Puebla Earthquake

Two major earthquakes occurred in Mexico during September 2017: a M_w 8.1 on September 7 off the southern coast of Chiapas and a M_w 7.1 on September 19 about 55 km (34 miles) south of the city of Puebla. The second event caused significant loss of life and damage in Mexico City, including the collapse of more than 40 buildings.[25] In mid-October 2017, ACI Committee 133 deployed a team with funding support from the NSF. With the assistance of faculty from Universidad Nacional Autónoma de México (UNAM) and Colegio de Ingenieros Civiles de México (CICM), the team surveyed RC buildings located in Mexico City. Most of the buildings surveyed were constructed prior to 1985, were five to 10 stories, and were comprised of RC framing with masonry infill. The most salient observation was that the affected structures were too flexible. Flexible RC frames without adequate transverse reinforcement lack the deformability to cope with large lateral drift demands. Continuous grade-to-roof infill walls were observed to increase stiffness and reduce drift, but these walls were seldom distributed in two directions on the floor plan. In most cases, continuous infill was present only along floor plan edges perpendicular to the street. In this direction, damage to the frame was infrequent and relatively minor. Continuous infill walls were rarely present parallel to the street, and in this direction building damage tended to be much more severe (Fig. 6).

Representatives of ACI 133 returned in January 2018 to conduct ambient vibration testing of 13 buildings, including five schools, to assess the dynamic properties of the buildings.

2017 Pohang Earthquake

On November 15, 2017, a M_w 5.4 earthquake struck Pohang, South Korea. Hundreds of houses and schools were damaged. In early December 2017, ACI Committee 133 deployed members to investigate the impacts of this earthquake on RC structures. Together with researchers from NCREE, nearby

South Korean universities and engineering firms (Chang Minwoo Structural Consultants and faculty/students from Seoul National University, Ulsan National Institute of Science and Technology, Kyungpook National University, Daegu University, and Gyeongnam National University of Science and Technology), the team documented both damaged and undamaged buildings over the course of 6 days. The team collected dimensions of structural elements to evaluate the Hassan Index as well as stiffness irregularities.[16] Of the 43 buildings with severe or moderate structural damage, 36 were "piloti" structures, residential buildings with three to four stories and an open first story for parking. The first-story structure comprised exposed RC columns with a single stairwell/elevator shaft of RC walls. Above the open first story, the structures included infill walls between residences. Architecturally, this configuration offered ample covered parking and sound-dampening between dwellings, but structurally it led to soft-story conditions that proved to be vulnerable to earthquake shaking as the first story sustained large drift demands. Security cameras captured dramatic video of the sudden failures of RC columns in such an apartment building.[27] Figure 7 shows the damage observed in two buildings.[28]

Fig. 7: Observed damage to RC structures in the 2017 Pohang Earthquake: (a) a first-story column; and (b) a structural wall in another building *(after Reference 28, licensed under CC BY 3.0)*

Fig. 8: Chirajara Bridge west tower failure sequence *(after Reference 29)*

2018 Chirajara Bridge collapse

On January 15, 2018, construction of the Chirajara Bridge, one of 47 bridges in a Colombian project to expand the Agencia Nacional de Infraestructura (ANI) highway from Bogotá to Villavicencio, was nearing completion when its west tower collapsed, claiming the lives of nine construction workers. With the approval of ANI, members of ACI Committee 133 visited the site on January 25-26 to collect information that could assist in the development of improvements in design recommendations for bridge structures. The team evaluated footage of the collapse (Fig. 8) and conducted on-site inspections using a spotting scope, cameras, and unmanned aircraft systems (UAS). A review of the design drawings revealed that the tower slab, which was apparently intended to act as a tie midway up the diamond-shape support towers, had insufficient longitudinal reinforcement to support the gravity loading condition estimated on the tower at the time of the collapse. Findings from the ACI Committee 133 team's investigation illustrate the importance of: 1) exceeding Code minimum reinforcement ratios in critical members to allow spread of inelastic deformations, thus avoiding brittle behavior as a result of strain concentrations; and 2) the peer-review process, specifically for complex structures. Details of the investigation can be found in Pujol et al.[29]

2018 Camp Fire

The November 8, 2018, Camp Fire burned over 150,000 acres (60,700 ha) in Butte County, CA, USA, resulting in the destruction of nearly 19,000 structures.[30,31] ACI Committee 133 deployed two members, one of whom was supported by NSF and the Natural Hazards Center, to collect data on the effectiveness of wildfire mitigation efforts with regard to schools and hospitals, and to investigate the performance of engineered structures throughout Paradise, CA, USA. The team visited 13 public and charter schools as well as 23 buildings on the Adventist Health campus in Paradise.

Typical commercial facilities consisted of RC or masonry wall structures with light-gauge steel joist roofs. One example was the Stratton Market, which collapsed due to the fire

Historical Disasters Examined in ACI Publications

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2000s:

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- See Reference 21.
- See Reference 29.

Fig. 9: Remains of buildings destroyed in the Camp Fire: (a) Stratton Market; and (b) Paradise Elementary School *(photos courtesy of Erica Fischer)*

Fig. 10: A damaged mid-rise RC-frame building in Albania

(Fig. 9(a)). One school building, Paradise Elementary School, had RC columns and timber framing. It also completely collapsed due to the fire (Fig. 9(b)). The ACI team also documented damage to a three-story residential building with RC framing. The fire caused buckling of the building's corrugated metal roof, cracking and spalling around flexural reinforcement in RC roof beams, and vertical splitting and spalling of third-story columns.

Data from the reconnaissance are now being curated, and a report is being prepared for publication in ASCE's *Natural Hazards Review*.

2019 Albania Earthquake

On November 26, 2019, a M_w 6.4 earthquake struck northwestern Albania. This earthquake was the strongest to hit Albania in more than 40 years. Cities such as Thumanë, Tirana, and Durrës suffered damage, but Durrës was hit hardest with several building collapses. A day after the event, ACI Committee 133 created a channel on the Slack messaging platform to share and discuss news within the committee, and it invited noncommittee members with firsthand knowledge to share their observations. Participants described typical construction practices and the seismic code used in Albania, and they provided estimates of the number of structures affected. Based on this information and information gathered from other organizations like EERI, ACI Committee 133 decided to deploy a team to Albania. ACI team members joined with researchers from Albania, Croatia, and Germany (Epoka University, Tirana, Albania; University of Osijek, Osijek, Croatia; and Bauhaus-Universität Weimar, Weimar, Germany) to document 55 buildings over the course of 4 days in January 2020. The team surveyed buildings that had RC frames as their main lateral resisting system. All buildings included unreinforced masonry infill walls (hollow clay bricks), and most also had ribbed or waffle slabs. Typical damage was in-plane or out-of-plane failure of nonstructural hollow clay brick walls (Fig. 10). In most cases, the hollow clay bricks were not connected to the RC frame. The team is in the process of uploading the collected data and preparing a manuscript about its findings.

External Coordination

Experiences gained through ACI Committee 133 deployments have illustrated the importance of partnering in the field with external researchers and organizations to leverage skill sets outside of the ACI committee. For example, during their second deployment to study the effects of the Puebla Earthquake in Mexico, ACI team members joined forces with researchers conducting terrestrial laser scanning (three-dimensional LiDAR scanning) of several buildings to assess their residual displacement and compare displacements with those predicted using nonlinear finite element models.[32] Teaming with other researchers and organizations can also help to maximize productivity in the field and reduce overhead for the organizations involved.

ACI Committee 133 members are exploring ways to better coordinate field deployments with governmental organizations (for example, the Federal Emergency Management Agency [FEMA] and the National Institute of Standards and Technology [NIST]) that conduct reconnaissance activities under statutory programs such as the National Earthquake Hazards Reduction Program (NEHRP), the National Windstorm Impact Reductions Program (NWIRP), and the National Construction Safety Team (NCST).

Developments

Through the course of eight deployments, ACI Committee 133 members have developed procedures for preparing teams to enter the field following major disasters. The committee has also worked to standardize data collection documents for describing building characteristics and damage.[20,22,23,26,28] Other recent activities include implementation of new technologies, such as UAS and LiDAR, made possible through collaboration with the Natural Hazards Engineering Research Infrastructure (NHERI) facility (commonly called the RAPID Facility: **https://rapid.designsafe-ci.org**).

ACI Committee 133 has also been exploring efforts to streamline post-processing of data collected in the field. One such effort involves using machine vision to automate structural damage detection in post-disaster images.[33] ACI Committee 133 continues to seek members and partners with an interest in advancing the approaches used for data collection and assessment of RC structural damage data to inform the evolution of ACI technical publications and their use worldwide.

Conclusions

Since its conception in 2013, ACI Committee 133 has deployed reconnaissance teams to eight areas affected by disasters. Members have surveyed more than 700 buildings and one bridge, collecting both qualitative and quantitative data (Table 1). During this time, the committee has streamlined its operating procedures, incorporated new technologies, and collected valuable data. Early deployments focused on reconnaissance of RC buildings affected by earthquakes. Because these disasters affect large regions with hundreds or thousands of buildings, they provide opportunities to collect building performance data across a wide spectrum of building configurations and damage levels. Data gained from these deployments have supported previously proposed measures for assessing the seismic vulnerability of structures,[16] and they have provided valuable new information about other aspects of RC behavior during earthquakes. They have also showcased the merits of working closely with local researchers and government entities, the merits of pre-deployment of "digital reconnaissance" to maximize productivity in the field, and the usefulness of UAS for surveying large areas or areas with limited safe access. More recently, the committee has begun deploying after other disasters, including a bridge collapse and a wildfire. These deployments have demonstrated to the committee different needs for collection of data after nonearthquake disasters. Interested readers are encouraged to attend ACI Committee 133 meetings at ACI Conventions and/or apply for membership.

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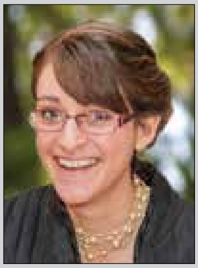

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