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Hurricane Otis
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EARLY ACCESS RECONNAISSANCE REPORT (EARR)

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PREFACE

The National Science Foundation (NSF) awarded an EAGER grant (CMMI 1841667) to a consortium of universities to form the Structural Extreme Events Reconnaissance (StEER) Network (see https://www.steer.network for more details). StEER was renewed through a second award (CMMI 2103550) to further enhance its operational model and develop new capabilities for more efficient and impactful post-event reconnaissance. StEER builds societal resilience by generating new knowledge on the performance of the built environment through impactful post-disaster reconnaissance disseminated to affected communities. StEER achieves this vision by: (1) deepening structural engineers' capacity for post-event reconnaissance by promoting community-driven standards, best practices, and training, as well as their understanding of the effect of natural hazards on society; (2) coordination leveraging its distributed network of members and partners for early, efficient and impactful responses to disasters; and (3) collaboration that broadly engages communities of research, practice and policy to accelerate learning from disasters.

Under the banner of the Natural Hazards Engineering Research Infrastructure (NHERI) CONVERGE node, StEER works closely with the wider Extreme Events consortium to promote interdisciplinary disaster reconnaissance and research. The consortium includes the Geotechnical Extreme Events Reconnaissance (GEER) Association and the networks for Interdisciplinary Science and Engineering Extreme Events Research (ISEEER), Nearshore Extreme Event Reconnaissance (NEER), Operations and Systems Engineering Extreme Events Research (OSEEER), Social Science Extreme Events Research (SSEER), Sustainable Material Management Extreme Events Reconnaissance (SUMMEER), and Public Health Extreme Events Research (PHEER), as well as the NHERI RAPID facility, the NHERI Network Coordination Office (NCO), and NHERI DesignSafe CI, curation home for all StEER products.

While the StEER network currently consists of the three primary nodes located at the University of Notre Dame (Coordinating Node), University of Florida (Southeast Regional Node), and University of California, Berkeley (Pacific Regional Node), StEER is currently expanding its network of regional nodes worldwide to enable swift and high quality responses to major disasters globally.

StEER's founding organizational structure includes a governance layer comprised of core leadership with Associate Directors for each of the primary hazards as well as the cross-cutting area of Data Standards, led by the following individuals:

Tracy Kijewski-Correa (PI), University of Notre Dame, serves as StEER Director responsible for overseeing the design and operationalization of the network and representing StEER in the NHERI Converge Leadership Corps.

Khalid Mosalam (co-PI), University of California, Berkeley, serves as StEER Associate Director for Seismic Hazards, serving as primary liaison to the Earthquake Engineering community.

David O. Prevatt (co-PI), University of Florida, serves as StEER Associate Director for Wind Hazards, serving as primary liaison to the Wind Engineering community.

Mohammad S. Alam (co-PI), University of Hawai'i at Manoa, serves as StEER Associate Director for Coastal Hazards, serving as a primary liaison to the coastal engineering community.

David Roueche (co-PI), Auburn University, serves as StEER Associate Director for Data Standards, ensuring StEER processes deliver reliable and standardized reconnaissance data suitable for re-use by the community.

This core leadership team works closely with StEER's Program Manager and Data Librarians in event responses, in consultation with its Advisory Boards for Coastal, Seismic and Wind Hazards.

ATTRIBUTION GUIDANCE

Reference to EARR Analyses, Discussions or Recommendations

Reference to the analyses, discussions or recommendations within this report should be cited using the full citation information and DOI from DesignSafe (these are available at https://www.steer.network/products).

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This material is based upon work supported by the National Science Foundation under Grant No. CMMI 2103550. Any opinions, findings, and conclusions or recommendations expressed in this material are those of StEER and do not necessarily reflect the views of the National Science Foundation. All authors and editors listed on the cover page participate as volunteer professionals. Thus, any opinions, findings, and conclusions or recommendations expressed herein are those of the individual contributors and do not necessarily reflect the views of their employer or other institutions and organizations with which they affiliate.

Special thanks to Spatial Networks for their ongoing partnership and generous support, making available, at no cost, the Fulcrum Community mobile platform for StEER Performance Assessments. The FAST appreciates the assistance of Nicolas Rojas Lopez (local guide), Dr. Jorge Hernandez Toral (drone operator), and Dr. Rigoberto Alejandro Moreno Vazquez (Comisión Federal de Electricidad Disaster Response Team and Universidad de Guadalajara).

The sharing of videos, damage reports and briefings via Slack by the entire NHERI community was tremendously helpful and much appreciated. StEER recognizes the efforts of the DesignSafe CI team who continuously supported and responded to StEER's emerging needs.

To access StEER products associated with past responses, please visit the StEER website: https://www.steer.network/responses

COMMON TERMS & ACRONYMS

Acronym	General Terms	Brief Description
--	DesignSafe	Data Repository
--	DesignSafe-CI	Academic Organization within NHERI
ASCE	American Society of Civil Engineers	Professional Organization
ASTM	American Society for Testing and Materials (now ASTM International)	Standards Body
ATC	Applied Technology Council	Professional Organization
BOCA	Building Officials and Code Administrators	Code Body
C&C	Components and Cladding	Common Wind Design Term
CBF	Concentric Braced Frames	Lateral Force Resisting System
CC-BY	Creative Commons Attribution License	Code/Standard
CESMD	Center for Engineering Strong Motion Data	Governmental Agency
CI	Cyberinfrastructure	Research Asset
CLPE	Critical Load Path Elements	StEER Term
CMU	Concrete Masonry Unit	Building Material
CPIC	Center for Public Interest Communication	Research Support Organization within University of Florida to study, test and apply strategic communication for social change
CWA	Central Weather Administration	Taiwan Governmental Agency
DBE	Design Basis Earthquake	Design Terminology
DEFS	Direct Applied Exterior Finish	Building Component
DEQC	Data Enrichment and Quality Control	StEER Term
DOI	Digital Object Identifier	Common Term
EARR	Early Access Reconnaissance Report	StEER Term
EERI	Earthquake Engineering Research Institute	Professional Organization
EEFIT	Earthquake Engineering Field Investigation Team	Professional Organization
EF	Enhanced Fujita Scale	Hazard Intensity Scale
EF	Equipment Facility	Academic Organization within NHERI
EIFS	Exterior Insulation Finish System	Building Component

FAA	Federal Aviation Administration	Governmental Agency
FAQ	Frequently Asked Questions	Common Term
FAST	Field Assessment Structural Team	StEER Term
FEMA	Federal Emergency Management Agency	Governmental Agency
FIRM	Flood Insurance Rate Maps	Regulatory Product
GEER	Geotechnical Extreme Events Reconnaissance	Academic Organization within NHERI
GPS	Global Positioning System	Measurement Technology
GSA	Government Services Administration	Governmental Agency
HVAC	Heating, ventilation and air conditioning	Building System
HWM	High Water Mark	Intensity Measure
HSS	Hollow Structural Sections	Building Material
IBC	International Building Code	Code/Standard
ICC	International Code Council	Code Body
IRC	International Residential Code	Code/Standard
ISEEER	Interdisciplinary Science and Engineering Extreme Events Research	Academic Organization within NHERI
LFRS	Lateral Force Resisting System	Common Seismic Design Term
LiDAR	Light Detection and Ranging	Measurement Technology
MCE	Maximum Considered Earthquake	Design Terminology
ME&P	Mechanical, electrical and plumbing	Building System
MMI	Modified Mercalli Intensity	Hazard Intensity Scale
MRF	Moment Resisting Frames	Lateral Force Resisting System
MWFRS	Main Wind Force Resisting System	Common Wind Design Term
NBC	National Building Code	Code/Standard
NEER	Nearshore Extreme Event Reconnaissance	Academic Organization within NHERI
NFIP	National Flood Insurance Program	Government Program
NHERI	Natural Hazards Engineering Research Infrastructure	Academic Organization within NHERI
NIST	National Institute of Standards and Technology	Governmental Agency

NOAA	National Oceanic and Atmospheric Administration	Governmental Agency
NSF	National Science Foundation	Governmental Agency
NWS	National Weather Service	Governmental Agency
OSB	Oriented strand board	Construction Material
OSEEER	Operations and Systems Engineering Extreme Events Research	Academic Organization within NHERI
PEER	Pacific Earthquake Engineering Research center	Academic Organization (Earthquakes)
PGA	Peak Ground Acceleration	Intensity Measure
PHEER	Public Health Extreme Events Research	Academic Organization within NHERI
PVRR	Preliminary Virtual Reconnaissance Report	StEER Term
QC	Quality Control	Oversight process
RAPID	RAPID Grant	Funding Mechanism
RAPID-EF	RAPID Experimental Facility	Academic Organization within NHERI
RC	Reinforced Concrete	Building Material
SAR	Search and Rescue	Standard Hazards Terminology
SGI	Special Government Interest	FAA Process
SLP	Surface-Level Panoramas	Measurement Technology
SMS	Short Message Service	Communication Modality
SPC	Storm Prediction Center	Governmental Agency
SSEER	Social Science Extreme Events Research	Academic Organization within NHERI
StEER	Structural Extreme Events Reconnaissance network	Academic Organization within NHERI
SUMMEER	SUstainable Material Management Extreme Events Reconnaissance	Academic Organization within NHERI
TAS	Testing Application Standard	Technical Standard
UAS/V	Unmanned Aerial Survey/System/Vehicle	Measurement Technology
USD	US Dollar	Standard Currency
USGS	United States Geological Survey	Governmental Agency
VAST	Virtual Assessment Structural Team	StEER Term
WS	Windshield Survey	Measurement Technology

EXECUTIVE SUMMARY

Hurricane Otis made landfall as a Category 5 hurricane near Acapulco, Guerrero, Mexico at 6:25 UTC (12:25 AM local time) on October 25, 2023, with an estimated wind speed of over 160 mph at landfall, surpassing Hurricane Patricia as the strongest landfalling Pacific hurricane on record. The hurricane led to 52 reported casualties and an estimated $12-$16 billion in damage. Reports suggest that over 98% of homes and around 80% of the hotels in Acapulco were damaged. Of the more than 5,800 commercial establishments damaged, over 4,000 were a total loss. The unprecedented scale of damage to single- and multi-story buildings in low-lying regions of Acapulco included dramatic failures of glazing, cladding, and roof surfaces. These failures extended to nearly every high-rise structure in the nearshore region.

Due to the special approvals needed for international missions, particularly given the safety concerns, StEER delayed the deployment of its small team for a rapid survey of Acapulco, Guerrero, Mexico until March 11 to 14, 2024. The mission focused on notable highrise failures near the landfall area; thus, it targeted the areas along the coastline of Acapulco Bay and neighboring Playa Diamante. Given the damage to upper stories of high-rise buildings and equipment restrictions, unmanned aerial systems were used as the primary rapid imaging platform to conduct free-flight surveys over specific geographies and imaging select high-rise buildings over their full elevation. In parallel, a limited number of in-depth structural performance assessments were conducted using StEER's Unified Assessment mobile application in Fulcrum platform. These efforts culminated in this Early Access Reconnaissance Report (EARR), StEER's second product from this event, providing an overview of Hurricane Otis, StEER's Level 2 response, and preliminary findings based on the observations generated by its Field Assessment Structural Team (FAST).

In general, the FAST observed: (i) extensive wind-induced failure of curtain walls and cladding systems in buildings along the coast of Acapulco in a variety of upwind exposures including open water, open terrain, suburban terrain, and urban canopies; (ii) widespread and complete damage propagation to interior contents (both wind and water ingress) ensuing from the failure of curtain walls and cladding systems, (iii) wind-induced brittle structural failures and partial collapse of low-rise commercial buildings and other structures. Based on these observations, StEER recommends further study in the topics of:

1. Elevated Hurricane Risk in a Changing Climate
2. Wind Speed-up Effects on Damage within Urban Canopies
3. Wind-Induced Dynamic Response of Buildings and Effects on Lateral Force Resisting Systems (LFRS) and Components and Cladding (C&C)
4. Wind Design and Retrofit Considerations of Predominantly Seismically-Designed Buildings
5. Risk Consistency Evaluations of Building Design Provisions for Multi-Hazard Regions
6. Wind and Seismic Design considerations for cladding, curtain wall systems and fenestrations of mid- to high-rise structures
7. Validating observations of multi-hazard demands

Collected data are hosted on the Fulcrum App (see Hurricane Otis Response Page) and will be published on DesignSafe under project PRJ-4231 for re-use by the community. All observations and findings provided in this EARR should be considered preliminary and are based on the limited scope of a Level 2 FAST. Due to the security concerns in the affected area and Level 4 travel advisory from the Department of State, StEER cannot elevate to a Level 3 response collecting in-depth performance assessments.

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Introduction

Hurricane Otis made landfall as a Category 5 hurricane near Acapulco, Guerrero, Mexico at 6:25 UTC (12:25 AM local time) on October 25, 2023, with an estimated wind speed of over 160 mph at landfall, surpassing Hurricane Patricia as the strongest landfalling Pacific hurricane on record (Reinhart and Reinhart, 2024). The impacts were exacerbated by Otis' rapid intensification from Tropical Storm to peak strength as a Category 5 hurricane in 15 hours (Reinhart and Reinhart, 2024), limiting evacuation and preparation efforts. The hurricane led to 52 reported casualties and an estimated $12-$16 billion in damage. Reinhart and Reinhart (2024) report that over 98% of homes and around 80% of the hotels in Acapulco were damaged. Of the more than 5,800 commercial establishments damaged, over 4,000 were a total loss. The unprecedented scale of damage to single- and multi-story buildings in low-lying regions of Acapulco included dramatic failures of glazing, cladding, and roof surfaces. These failures extended to nearly every high-rise structure in the nearshore region. Over 100 medical clinics were damaged, and the Acapulco International Airport suspended operations due to damage to its control tower and other facilities. Loss of the airport, roads, and even port facilities limited access to the affected coastal areas.

In response, StEER activated its **Virtual Assessment Structural Team (VAST)** for Hurricane Otis on October 25, 2023 to assemble information on the event from public sources and lead authorship of the **Preliminary Virtual Reconnaissance Report (PVRR)** released November 16, 2023 (Dang et al., 2023). Informed by this report, StEER escalated its response to Level 2, activating a **Field Assessment Structural Team (FAST)** to travel to the impacted area. Special travel approvals required due to the security situation in Guerrero delayed their mission until March 11-14, 2024. This **Early Access Reconnaissance Report (EARR)** serves as the primary product of this Level 2 response to Hurricane Otis and is intended to:

- Introduce the data collection methodology and chronology,
- Summarize key observations from the field, and
- Provide recommendations for continued study of this event by StEER and the wider natural hazard engineering community.

1. Field Data Collection Strategy

StEER's Level 2 response was intended to rapidly survey Acapulco, Guerrero, Mexico from March 11 to 14, 2024. Table 2.1 reports the team composition. Given the damage to upper stories of high-rise buildings, and due to the fact that equipment from the NHERI RAPID EF could not be brought into Mexico due to the Level 4 State Department warning, locally-operated unmanned aerial systems (UAS), two Mavic Air 2S unmanned aerial vehicles (UAVs), were used as the primary rapid imaging platform. Data collection modes for the UAS included:

- Rapid Survey: Free-Flight surveys over specific geographies;
- Case Study: Panoramas (wraparounds moving vertically upward) on select high-rise buildings.

The mission focused on notable high-rise failures near the landfall area and was centered on the areas along the coastline of the main Acapulco Bay and neighboring Playa Diamante area. Puerto Marques Bay, a cove sheltered between the main Acapulco Bay and Playa Diamante, was not assessed. Opportunistic sampling was employed to assess structures with unique and systematic failure patterns. Other residential areas further inland and towards the historic downtown Acapulco beaches could not be surveyed due to security concerns.

Performance Assessments were also conducted using StEER's Unified Assessment mobile application implemented in Fulcrum platform. Basic Assessments (BA), which are the lowest fidelity-level performance assessment under StEER's tiered performance assessment protocol, were performed to record high-level global damage assessments of buildings to a) complement the UAS data, b) maximize the number of records that could be acquired in the available window of time, and c) document damage in targeted buildings located in the no fly zones near the Acapulco Airport and Mexican Navy Facilities. A typical assessment included: 1) collecting clear photographs from multiple perspectives, 2) accurately geo-locating the assessments over the target building or structure, 3) filling out site-specific fields that require information only visible on-site, and 4) noting unique features of structures that would affect performance and not be otherwise visible from supplemental data sources. However, as per the StEER response criteria for Level 2 responses, detailed forensic investigations were not the primary objective; instead, focus was placed on rapidly capturing ephemeral imagery of the affected area under strict time constraints.

Moreover, since Performance Assessments were primarily collected via Opportunistic Sampling, the collected records should not be assumed to be representative of all affected structures. For example, using these records to develop fragility functions would not be appropriate unless further analysis confirmed that the samples are representative of the broader inventory. However, the collected imagery can be reused for hypothesis-driven research and to inform the collection of additional in-depth forensic assessments as part of a Level 3 response or other field investigations. The collected data are hosted on StEER Unified App in Fulcrum platform (see Hurricane Otis Response Page) and will be published, after data enrichment and quality control, on DesignSafe under project PRJ-4231 for re-use by the community.

Table 2.1: Level 1 Field Assessment Structural Team (FAST).

Member	Affiliation	Assignment
Juan Antonio Balderrama Garcia Mendez	The University of Texas at Arlington	FAST Lead
Sergio Daniel Ibarra Cedilo	The University of Texas at Arlington	FAST Member
Jorge Hernandez Toral	Drones México: Automatización Industrial	UAS Pilot

2. Chronology of Data Collection

Table 3.1 summarizes the geographical coverage and chronology in terms of neighborhoods or *colonias* (i.e., political subdivisions within a Mexican municipality) included in StEER's Level 2 damage assessment efforts; the table assigns each neighborhood an area identifier and provides the type of assessment tools used for data collection. Figure 3.1 overlays the geographical coverage in a satellite image of the region. Fulcrum records for damage assessments in the region, including buildings, public infrastructures (e.g., light poles, airport facilities), and free-standing walls, are located in Figure 3.2. A total of 91 buildings were assessed and grouped into the 20 different clusters/blocks identified in Table 3.2. The basis for cluster designation included i) the Mexican urban planning subdivisions *manzanas* (i.e., blocks in the United States), ii) potential upwind flow features or similar damage patterns identified by the team as interesting for further study (scientific research basis), iii) data acquisition mode, iv) building typology and damage features, and v) random interruptions during acquisition of data via the UAS (e.g., the drone running out of battery, the team stopping to buy water, short interviews with the locals). Figure 3.3 provides a graphic depiction of the clusters overlaid on the region's map. These efforts culminated in 102 performance assessments (PA) in Fulcrum, 45 UAS videos, and almost 4,000 UAS photographs.

Table 3.1: Deployment itinerary and geographic coverage.

Date	Geographic Coverage (*Colonias*)	ID	UAS	PA
Monday March 11, 2024	Colonia Plan de los Amates (aka Vicente Guerrero 200)	A01		●
	Colonia Aeropuerto	A02		●
Tuesday March 12, 2024	Fraccionamiento Tres Vidas	A03	●	●
	Colonia Aeropuerto	A02	●	●
	Fraccionamiento Magallanes (Main Acapulco Bay)	A04	●	●
	Colonia Deportivo (Main Acapulco Bay)	A05	●	●
	Colonia Icacos (Main Acapulco Bay)	A06	●	●
	Colonia Granjas del Marques (Diamante Area)	A07	●	●
Wednesday March 13, 2024	Colonia Playa Diamante (Diamante Area)	A08	●	●
	Colonia Granjas del Marques (Diamante Area)	A07	●	●
Thursday March 14, 2024	Colonia Playa Diamante (Diamante Area)	A08		●
	Colonia Aeropuerto	A02		●

Table 3.2: Building clusters, geographic area, and date of assessment.

ID	Name	Geographic Area (Colonia)	ID	Date
C01	Hotel One	Plan de los Amates	A01	3/11
C02	ACA Airport/Road to Hotel One	Aeropuerto	A02	3/11
C03	Tres Vidas/El Manglito	Fraccionamiento Tres Vidas	A03	3/12
C04	Aeropuerto/Tres Vidas (No Fly)	Aeropuerto	A02	3/12
C05	Krystal Beach Cluster	Fraccionamiento Magallanes	A04	3/12
C06	Catedral Cristo Rey	Fraccionamiento Magallanes	A04	3/12
C07	Centro de Convenciones	Deportivo	A05	3/12
C08	Playa Icacos	Icacos	A06	3/12
C09	Granjas del Marques/Turtle Dunes	Granjas del Marques	A07	3/12
C10	Road to Diamante Beach	Playa Diamante	A08	3/13
C11	Maroa	Playa Diamante	A08	3/13
C12	Vidanta Mayan	Playa Diamante	A08	3/13
C13	OXXO/Aquarelle/Romanza	Playa Diamante-Granjas del Marques	A07-A08	3/13
C14	Masonry Building Cluster	Granjas del Marques	A07	3/13
C15	Marena	Granjas del Marques	A07	3/13
C16	Hotel Princess	Granjas del Marques	A07	3/13
C17	Tennis Arena GNP	Granjas del Marques	A07	3/13
C18	Costera de las Palmas No Fly	Playa Diamante	A08	3/14
C19	Barra Vieja Beach Front No Fly	Aeropuerto	A02	3/14
C20	Barra Vieja Street Front No Fly	Aeropuerto	A02	3/14

Figure 3.1. Designated areas for geographic coverage (NHC hindcast hurricane track in yellow).

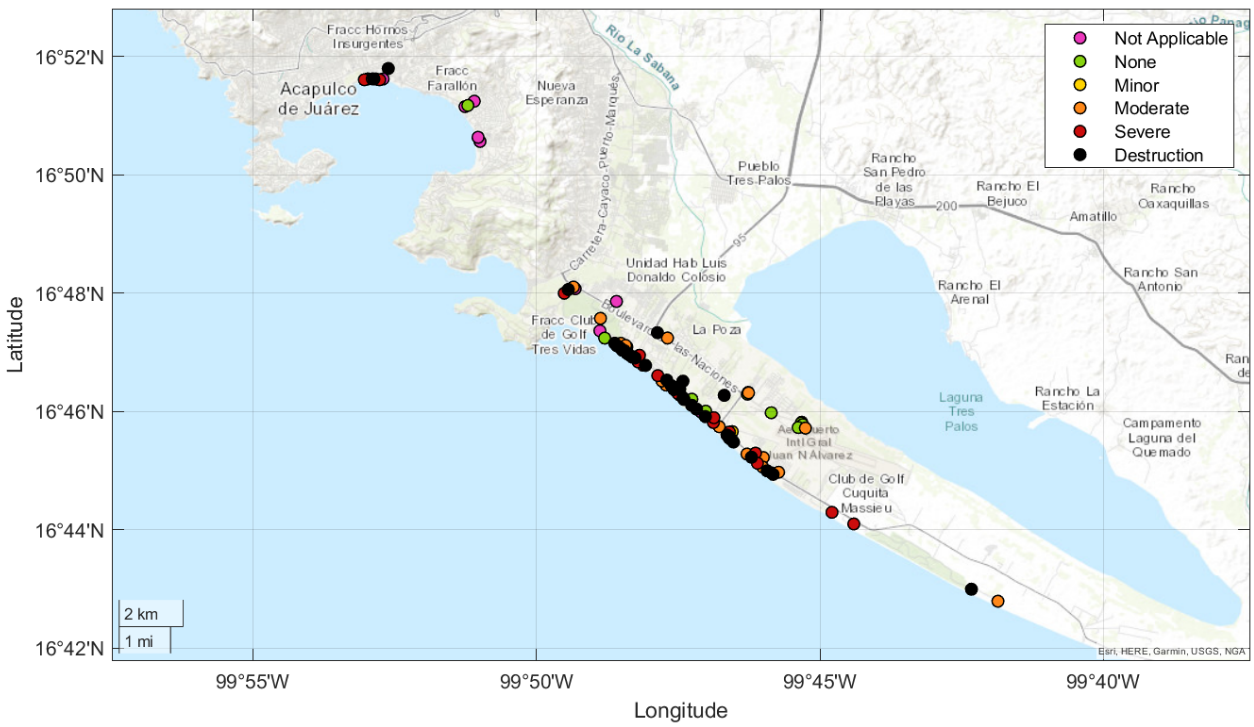


Figure 3.2. Locations of the individual performance assessments.

a) Clusters in the Main Acapulco Bay

b) Clusters in the Diamante, Barra Vieja, and Tres Vidas Beaches

Figure 3.3. Locations of clusters of buildings assessed.

3. Observed Performance

Hurricane Otis produced catastrophic damage in the Acapulco region. This section summarizes observations of the wind performance of buildings obtained during the FAST and includes i) mid- and high-rise residential buildings, ii) low-rise residential buildings, and iii) low-rise commercial buildings. The post-disaster assessment of the clusters focused on wind-induced damage to the building envelope, components and cladding (C&C), and structural systems. The data is presented in its raw form and has not undergone any quality assurance or detailed analyses; thus, the assessments herein are solely based on the opinions of the FAST members and photos are provided for illustrative purposes. It is also important to note that since the field data collection occurred approximately 20 weeks after the hurricane, damaged elements and debris had been cleared from some structures in preparation for repairs, so the exact condition of the damaged elements was not known.

In general, damage to the building envelope of low-rise commercial and mid- and high-rise residential buildings was severe; during the assessment most buildings were found to be at the equivalent of a “rough framing” stage of construction with a) an undamaged primary structural system, b) a destroyed or demolished building envelope, and c) ruined finishes and building contents. Main structural systems of several low-rise commercial buildings were damaged; partial or full structural collapses were observed in some cases. Engineered low-rise residential buildings, exclusively in the Diamante and Barra Vieja areas, were subjected to less intense damage and were assessed for performance comparisons with mid- and high-rise buildings. Table 4.1 groups the observed damage into eight categories. Damage (induced by wind pressures, wind borne debris impact, or water penetration) to the building envelope and nonstructural components rendered most buildings unusable and resulted in substantial economic losses. Recurrent damage of elements within the categories in Table 4.1 was observed during the FAST.

Table 4.1: Damaged elements and categories

Roof C&C	**Wall C&C**	**Parapet & Guardrail**	**Overhangs/Exterior Soffit/False Ceiling**
1) Spanish clay roof tile 2) Flat clay roof tile 3) Standing seam metal roof panels 4) Steel roof purlins	1) Windows 2) Sliding doors 3) Glass envelope 4) Louver ventilated envelope 5) Latticed steel envelope 6) Cement board + cold formed steel studs envelope 7) Cement board + backing brick masonry wall envelope 8) Alucobond + secondary steel structure 9) PBR wall panel + steel wall girts	1) Parapet (cement board + cold formed steel studs) 2) Parapet (cement board parapet on secondary steel structure) 3) Guardrail (cement board + cold formed steel studs) 4) Guardrail (glass) 5) Guardrail (metallic) 6) Guardrail (masonry)	1) Balconies’ underside (gypsum or cement board) 2) Ceiling of stairways open to exterior (gypsum or cement board) 3) Ceiling of corridors open to exterior (gypsum or cement board)
Arch. Features	**Penthouse/Appendage/Canopy**	**Non-Structural Components and Building Content**	**Utilities**

1) Steel sheet + secondary steel structure 2) Cement board + secondary steel structure	1)Roof cladding (membranes, metallic deck) 2)Wall cladding	1) False ceiling (gypsum or cement board) 2) Interior partitions (gypsum board) 3) Appliances	1)Sewage plumbing system 2)Drainage plumbing system 3)Potable water distribution system 4)Elevator systems 5)Air conditioning systems 6)Electrical wiring systems 7)Mechanical and electrical rooms

3.1. Mid- and High-Rise Buildings

Mid- and high-rise residential buildings in the Acapulco region sustained extensive wind-induced damage to the building envelope and façade systems. The types of exterior wall cladding systems implemented in the mid- and high-rise residential buildings assessed during the FAST include i) veneer walls, ii) curtain walls, and iii) infill walls. Most buildings combined the use of these three types of exterior wall cladding systems throughout their various elevations. Table 4.2 lists the assemblies identified within these wall cladding systems; every building implemented at least two of the assemblies listed in Table 4.2.

Table 4.2: Wall cladding system assemblies identified

Wall Assemblies Common in Living Areas	Wall Assemblies Common in Service Areas (e.g., Machine Rooms and Corridors/Stairs)
● Glass windows and glass sliding doors, ● Glass panel curtain wall, ● Glass panel infill wall, ● Precast concrete panel curtain wall, ● Direct applied exterior finish (DEFS) curtain walls, ● Exterior insulated & finish (EIFS) curtains, ● Metallic panel curtain wall over secondary light gauge HSS steel structure, ● Stucco veneers directly adhered on: ○ Concrete masonry infill walls, ○ Reinforced concrete shear walls, ● Stucco finished cement board veneers on: ○ Concrete masonry infill walls, ○ Cold formed steel stud infill walls, ○ Cold formed steel stud curtain walls, ○ Light gauge HSS secondary structure, ● Exterior stucco finished cement board veneer on cold formed steel stud or EIFS curtain walls with interior infill wythe via: ○ Concrete masonry units, ○ Clay brick masonry units,	Ventilated façades consisting of: ● Perforated/lattice metallic panel curtains, ● Metallic louver panel curtains, ● Metallic louver panel infills, ● Perforated/lattice precast concrete panels over structural steel HSS elements, ● Perforated, stucco finished cement board veneer over cold formed steel stud walls, Utilities shaft consisting of: ● Metallic louver panel curtains over mechanically extruded clay brick masonry infill wall supporting pipes, ● Stucco finished cement board veneers on light gauge HSS secondary structure.

○ Extruded clay brick masonry units, ● Autoclaved aerated concrete (AAC) units.	

Damage to exterior wall cladding systems partially revealed components of the main structural systems in most buildings. Lateral force resisting systems (LFRS) observed in mid- and high-rise buildings assessed include a) reinforced concrete moment resisting frames and shear walls (Figure 4.1.1), b) structural steel moment resisting frames, braced frames, and buckling restrained braced frames (Figure 4.1.1), and c) composite systems (structural steel braced frames with composite columns, Figure 4.1.2). Several of the structural steel and composite systems implemented seismic dampers. The most common use of seismic dampers was metallic yielding energy dissipation devices in Concentric Braced Frames (CBFs, inverted Vs) with composite or plain steel columns; in some cases, the seismic dampers were discontinued on the top floors retaining only the CBFs as the LFRS of the upper levels of the building. A dominant structural system or construction material was not identified. Floor systems observed were either reinforced concrete joist systems lightened with expanded polystyrene blocks or composite corrugated steel deck; solid slabs were observed in some overhangs. The team was unable to identify whether interior bays used solid slabs or post-tensioned floor systems due to limited access and visibility. The FAST team did not detect damage to the floor structural systems and the LFRS of the assessed buildings.

Figure 4.1.1. Examples of Reinforced Concrete (RC) and Structural Steel LFRS in Acapulco (Source: FAST).

Figure 4.1.2. Examples of LFRS with Composite Columns in Acapulco (Source: FAST).

Engineering the lateral force resisting systems in sites subjected to multiple hazards like Acapulco requires balancing of potentially contradictory design objectives. A common strategy in earthquake resistant building design involves optimization of the seismic effective weight to reduce the earthquake-induced inertial forces and concentration of gravity loads on columns of the LFRS to mitigate overturning and uplift at their foundation. In contrast, an increase in the building's mass has minor effects in the intensity of the wind-induced forces on the LFRS; in fact, an increase in the building's mass can contribute to an increase in the resistance to global overturning. However, seismic and wind are not the only parameters considered in the definition of the engineering objectives; additional site-specific design parameters can shift the engineer's strategy, e.g., soils with low bearing capacity would require optimization of the building's weight regardless of the wind or seismic design objectives. Nevertheless, given the high seismic acceleration parameters of the region, the FAST members expected widespread adoption of lightweight exterior and interior wall systems to minimize the seismic effective weight. However, implementation of several of the exterior wall systems listed in Table 4.2–e.g., stucco finished masonry infill walls and double wythe walls with external lightweight systems and internal masonry wythes–in luxury apartments in the assessed residential complexes does not reflect prioritizing the minimization of the seismic effective weight to reduce the earthquake-induced inertial loads. The assessment team had observed these construction details in other projects along the multi-hazard-prone Mexican Pacific Coast (Puerto Vallarta, Manzanillo, Mazatlan, and Acapulco) as consumer preferences in this luxury market sector drive the use of "solid/hard" walls regardless of implications towards the seismic effective mass and the cost of the structure. This preference perpetuates the stereotype that light weight partition systems are of lower quality, even though the weight, "hardness", and "solid" feel of wall assemblies are not related to the cladding system's strength or structural performance, and hinders their implementation in the building stock in Mexico. Regardless, "solid/hard" and lightweight building envelope systems were severely damaged in most of the assessed mid- and high-rise buildings.

The mid- and high-rise residential buildings dominating Playa de Barra Vieja, Playa Diamante, Playa Revolcadero, and the main Acapulco Bay sustained extensive wind-induced damage. Observations in this section focus on the a) **architectural features of the building façade**, b) **components & cladding (roof and walls)**, c) **non-structural components** and **building contents**, and d) **penthouses**, **appendages, and canopies**.

Observations of buildings in Clusters 11-13, 15-16, and 18-20 of areas A07 and A08 are representative of the systematic damage sustained by mid- and high-rise buildings in the region. This section uses the buildings in these clusters to summarize the FAST observations. Clusters 11 to 16, exempt from no-fly regulations, contain observations collected via UAS and handheld devices and thus result in the most complete datasets. Figure 4.1.3 identifies the areas enclosed by Clusters 11-16 and 18-20 and dominated by mid- and high-rise buildings in the Diamante and Barra Vieja Beaches. Cluster 14 is included in Figure 4.1.3 as mid-rise buildings assessed in this cluster were subjected to less severe damage relative to the rest of the buildings in the area. Precise locations and imagery sources are provided in the Appendix.

Figure 4.1.3. Limits of Clusters 11-16 and 18-20 (Basemap Source: [Google Maps]()).

Figure 4.1.4 superimposes a wind compass rose over a close up of a satellite image of the eight towers in Cluster 13: Oasis, Costera de las Palmas 128, Aquarelle, Romanza, Amarinthos 1 and 2, Torre Playa Diamante, and Maranda (from East to West). The northeast and southwest fetches were, respectively, mostly homogeneous open terrain and open water exposures. Winds approaching from the southeast and northeast would have been subjected to interaction with closely spaced mid- and high-rise buildings similar to those of an urban canopy in dense urban areas resulting in complicated flow features (e.g., channeling, shielding) around the buildings. The exposures of Clusters 11-13, 15-16, and 18-20 in the Diamante and Barra Vieja area are similar to that shown in Figure 4.1.4. The Isla Roqueta Mexican Navy station (about 7 miles WNW from the center of Cluster 13) recorded maximum winds from the 30°-120° window (see Figure 2.3 of Dang et al. 2023). Both Cluster 13 and the Isla Roqueta weather station were within the right eyewall of the hurricane at its closest point and thus could be expected to have been subjected to similar wind velocity profiles.

Figure 4.1.4. Cluster 13 Aerial Image overlaid with wind compass (Basemap Source: [Google Maps](#)).

Figure 4.1.5 shows perspective views from the street of the eight towers: Oasis, Costera de las Palmas 128, Aquarelle, Romanza, Amarinthos 1 and 2, Torre Playa Diamante, and Maranda in Cluster 13 pre- and post-Hurricane Otis. Figures 4.1.6 and 4.1.7 together present general views from the beach of the eight towers: Maranda, Torre Playa Diamante, Amarinthos 1 and 2, Romanza, Aquarelle, Costera de las Palmas 128, and Oasis in Cluster 13 pre- and post-Hurricane Otis.

Figure 4.1.5. Cluster 13 NE elevation landward views; (top) before Hurricane Otis (Source: Google Street View) & (bottom) post Hurricane Otis (Source: FAST).

Figure 4.1.6. Cluster 13 SW elevation seaward views; (top) before (Source: Google Street View); (bottom) after Hurricane Otis (Source: FAST).

Figure 4.1.7. Cluster 13 SW elevation seaward views; (top) before Hurricane Otis (Source: Google Street View); (bottom) after Hurricane Otis (Source: FAST).

Figures 4.1.4 to 4.1.7 illustrate the wind flow path regimes upwind of the building site (far-field flow and near-field flow). All beachfront building clusters assessed in Playa de Barra Vieja, Playa Diamante, and Playa Revolcadero were subjected to flow interacting with four upwind conditions: i) open water, ii) open terrain, iii) suburban terrain, and iv) urban canopies generated by the strip of clusters with closely spaced mid- and high-rise buildings parallel to the beach. Figures 4.1.4 to 4.1.7 also illustrate the significant objects in proximity to the buildings in Cluster 13 and provide a reference for studies on this cluster's performance under extreme wind loads, including shielding and channeling effects in an urban canopy.

Architectural features of the façade and their supporting secondary structures were destroyed in most mid- and high-rise beach front buildings assessed. These features include aesthetic elements and finishes, shading devices, louvers, and lattice walls. Figure 4.1.8 depicts damage to architectural features and the supporting secondary steel structures of the Marena building in Cluster 15. Marena's architectural fins (6 thin metal sheet cladding elements supported by light gauge HSS structures) were extensively damaged by wind induced pressures and wind-borne debris. Damage in the field zones of the building's walls was lower than that in the corner zones.

Figure 4.1.8. Marena (Cluster 15) seaward and landward elevations views; (top, left) before Hurricane Otis view of the seaward SW elevation (Source: Google Street View); (bottom, left) before Hurricane Otis view of the landward NE elevation (Source: Google Street View); (top, right) after Hurricane Otis view of the seaward SW elevation (Source: FAST); (bottom, right) after Hurricane Otis view of the landward NE elevation (Source: FAST).

Components and cladding (roof and wall) were destroyed or severely damaged in most mid- and high-rise beach front buildings assessed. Elements grouped in these categories for the purpose of performance assessment include roof cladding, roof assemblies, wall cladding, wall assemblies, and the secondary structures of roof and wall assemblies.

Figure 4.1.9 depicts damage to flat clay roof tile cover. Flat clay roof tile is a typical (traditional) component of roof cover waterproofing systems in low rise building construction in Mexico; nevertheless, it introduces a higher seismic effective weight to the building. Mortar adhesive is used to attach tiles to the roof slab's concrete finished surface. Failure of the tile to slab bond due to tensile uplift forces is depicted in Figure 4.1.9.

Figure 4.1.9. Roof cover (Flat Clay Roofing Tile) damage at Torre Uno Condominio in Cluster 12 (Source: FAST).

Figures 4.1.10 and 4.1.11 show damage to the wall cladding and building envelopes at Maroa (Cluster 11) and Solar Ocean (Cluster 15), respectively. The damage to the Maroa building was so extensive that the assessment team initially thought the building was still in construction; however, construction of the building had been recently concluded (the most recent photograph of the complex from Google Street view, dated August 2021, shows the buildings in a near completion phase). The damaged elements had clearly been completely removed from the structure in preparation for reconstruction. The pre-Otis image in Figure 4.1.10 is a rendering from the developer's website. Wall assemblies of Solar Ocean and its neighbor Costa Bamboo consisted of double wythe walls with a clay, jumbo format, mechanically extruded brick internal wall and an external wythe of cement board cladding supported over cold formed steel studs. Use of this construction detail in the luxury apartments in these complexes does not reflect prioritizing the minimization of the seismic effective weight to reduce the earthquake-induced inertial loads. Regardless, the double wythe assemblies in Solar Ocean and Costa Bamboo were, respectively, completely destroyed and extensively damaged.

Figure 4.1.10. Maroa (Cluster 11) loss of wall cladding and building envelope; (top) rendering (Source: https://maroadiamante.mx/); (middle) before Hurricane Otis on August 2021 view of the NE elevation (Source: Google Street View); (bottom) after hurricane Otis view of the SW elevation, after removal of damaged elements (Source: FAST).

Figure 4.1.11. Wall building envelope damage at Solar Ocean in Cluster 15 (Source: FAST).

Figure 4.1.12 depicts the damage sustained by the non-structural components and the building's contents of Condominio Laguna Towers (Cluster 11). Wind pressure- and water-induced damage rendered all contents unusable. These observations were recurrent in nearly all buildings assessed.

Figure 4.1.13 presents damage to the penthouse, appendages, and canopies of Torre Playa Diamante (Cluster 13). Canopies, appendages, and penthouse components and cladding in the assessed buildings featuring amenities were destroyed. Identifying this type of damage during the FAST was not possible as the team was not aware that there had even been a penthouse; comparison of pre-Hurricane Otis images with those obtained during the FAST was necessary.

In general, damage to the building envelope of beachfront mid- and high-rise buildings was severe. During the assessment most buildings were equivalent to a "rough framing" stage of construction with a) an undamaged main structure, b) a destroyed building envelope, and c) ruined finishes and building contents that require demolition. Figure 4.1.14 presents a view of buildings inland in Cluster 14 and across the street from Clusters 13 and 15 depicting less intense damage to the building envelopes relative to the beachfront buildings. In general, the buildings inland from Clusters 13 and 15 have smaller windows and interstory heights and appear to have performed better than the beachfront buildings. The FAST was not able to identify the type of material and construction system for the envelope of structures with minor damage; thus, comparisons of partition and envelope system performance between the inland and beach-front buildings are not possible with the available information. Buildings in Cluster 14 have less privileged views compared to the beachfront clusters and appear to exhibit windows, sliding doors, and cladding assemblies with smaller clear spans that could have contributed to the less severe damage observed.

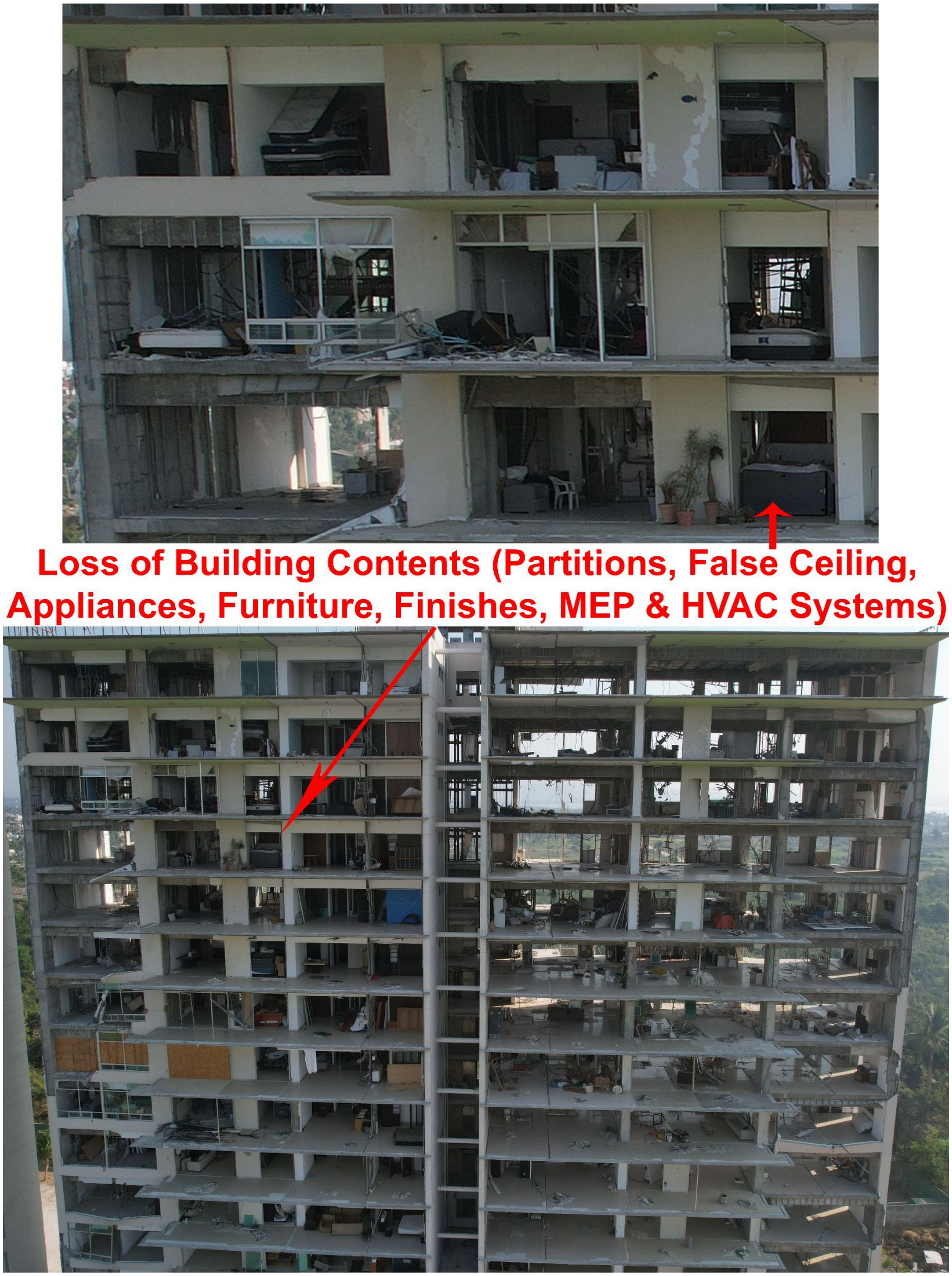


Figure 4.1.12. Damage to Building Contents at Condominio Laguna in Cluster 11, fairway view (Source: FAST).

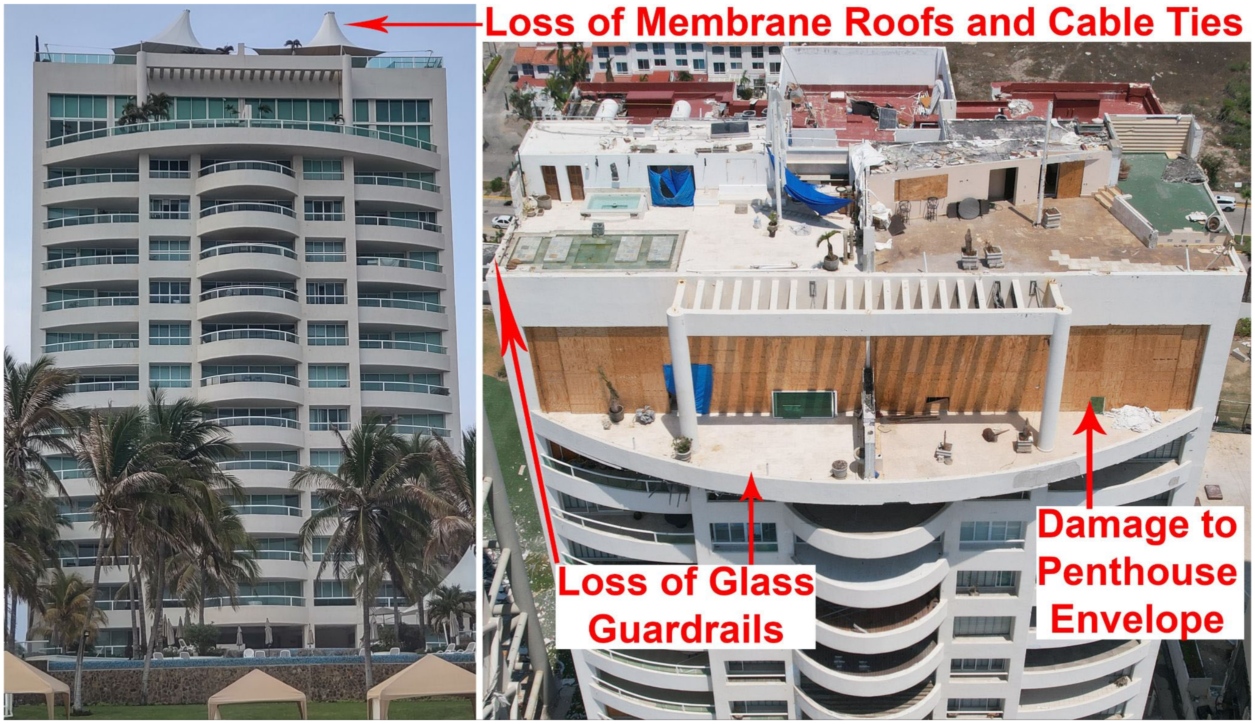


Figure 4.1.13. Torre Playa Diamante (Cluster 13) damage to penthouse and appendages, view of the SW, beachfront, elevation; (left) before Hurricane Otis (Source: Google Street View); after Hurricane Otis (Source: FAST).


Figure 4.1.14. Overall view of buildings inland from Clusters 13 and 15 (Source: FAST).

3.2. Low-Rise Residential

Non-engineered low-rise residential buildings, including mobile homes and trailer parks, were not within the scope of this assessment. Instead, the report focuses on *engineered low-rise* *residential buildings* in the surveyed areas either sustained a) similar damage to the building envelope and components & cladding as the mid- and high-rise buildings in Section 4.1 or b) minor damage in the building envelope and components & cladding and were only assessed to provide a reference for comparison of building envelope system performance across occupancies. Ambitious architectural features, e.g., large spans for wall assemblies, cladding systems, and windows/sliding doors, were detected in the low-rise buildings that sustained damage similar to the mid- and high-rise buildings. Most of the engineered low-rise buildings assessed as having minor damage did not have such ambitious architectural features. The low-rise buildings with damage similar to mid- and high-rise buildings also had lateral systems analogous to their taller counterparts (moment resisting frame systems and building frame systems per the ASCE 7-Chapter 12 general LFRS categories), whereas low-rise buildings with minor damage had fundamentally different lateral systems (bearing wall systems per the ASCE 7 general LFRS categories). As moment resisting frame systems prize open spans and clear views, it is unsurprising that they would use similar envelope systems and therefore sustain similar severity of damage across all heights surveyed.

Figure 4.2.1 depicts extensive damage to the building envelope and components & cladding of a 2-story accessory building of the residential complex Del Mar Tres Vidas in Cluster 03. The building envelope system in this building was not part of the LFRS for seismic loads (reinforced concrete moment resisting frames). Observations for this building are consistent with those presented in section 4.1.

Figure 4.2.2 shows minor damage to the building envelope and components & cladding of the single family engineered homes in the Barra Vieja area. The minor damage was concentrated in the windows (likely due to impact of wind-borne debris) and roof tiles. Construction type and damage to low-rise residential single-family housing in the assessed areas (tourist areas of Diamante and Barra Vieja) is not representative of the lower income areas of the region that were severely affected by the hurricane but not accessible to the FAST. These observations also applied to multi-family low rise residential buildings (2-5 stories) with construction typology similar to that of buildings eligible for government mortgage sponsored programs (e.g., INFONAVIT). INFONAVIT-style construction, either single- or multi-family, implement reusable aluminum formwork to satisfy the demands of mass housing campaigns. The characteristic structural system of cast in place reinforced concrete bearing walls serves as both the LFRS and the building envelope (Figures 4.2.2 and 4.2.3 present examples of multi-family INFONAVIT style complexes with minor damage in the Diamante and Barra Vieja areas).

Figure 4.2.1. Damage to building envelope and components and cladding of accessory building (Source: FAST).

Figure 4.2.2. Minimum damage to building envelope and components and cladding of single-family homes in the Barra Vieja area; (left) after Hurricane Otis (Source: FAST); (right) before Hurricane Otis showing typical architectural features (Source: Google Street View).

Figure 4.2.3. Examples of INFONAVIT-style construction utilizing reinforced concrete bearing walls as both the LFRS and the building envelope. Both the top and bottom images are representative of multi-family complexes just south of the airport (Source: FAST).

3.3. Low-Rise Commercial

Low-rise commercial buildings throughout the region were extensively damaged during Hurricane Otis. There are a large number of these types of buildings with extensive damage beyond the assessed clusters and throughout all of the Acapulco region. Clusters 01, 02, and 09 in the Diamante area commercial corridor (Blvd. de las Naciones) were easily accessible during the survey of the neighboring beachfront districts. Damaged buildings housed small businesses, large corporations, and public facilities. There is extensive variation among the building types within this category as the use of the buildings dictate the architectural layout, geometric features, and building characteristics (e.g., enclosure classification). The uses of the buildings subjected to extensive damage include:

- Wholesale Distribution and Storage:
    - Distribution centers (e.g., Bimbo and Grupo Modelo warehouses)
    - Self-storage facilities

    - Wholesale supply businesses (e.g., WalMarts, Sam's Club, Chedraui, Soriana)
    - Contractors plant, shop, and/or storage yards
- Transportation
    - Passenger Terminal (e.g., Estrella Blanca Bus Station and Acapulco Airport)
- Manufacturing
    - Concrete batch plant (e.g., Holcim)
    - Small-scale manufacturing/assembly (e.g., aluminum/window, carpentry shops)
- Industrial services
    - Flex, Office, or Commerce; Building maintenances/service; Medical laboratories
    - Machinery rental
- Retail
- Restaurants
- Auto Sales, Equipment, Repair (dealerships, car wash, gas stations, repair shops)
- Health Care Facilities (e.g., AA rehabilitation center, Insabi public healthcare center)
- Schools, Fire stations, and Red Cross facilities

The damage to these types of low-rise commercial buildings, in general, was focused on i) the lateral force resisting system (LFRS), ii) the gravity system, iii) components & cladding, and iv) the building contents. The enclosure classification was either open or enclosed; the perception of the FAST members was that open buildings were subjected to more severe damage than enclosed buildings based on the higher proportion of partial or complete collapses observed.

- The KIA car dealership, Multiplaza las Palmas shopping center, and Centro Comercial Harbour in the Diamante area were severely affected (Figures 4.3.1-4.3.3). The Multiplaza las Palmas (Fig. 4.3.1) sustained wind-induced collapse of a section of the main structure, extensive loss of cladding, and failure of the secondary structure (wall girts and roof purlins). A complete bay (purlins, truss, and columns) collapsed in this building (refer to the bottom right corner of Figure 4.3.1). The partial collapse observation represents a brittle failure of the LFRS of the building. The relative magnitudes of seismic- and wind-induced design loads and the differences in the hypothetical bases and objectives of the LFRS design approaches (reduced seismic load inelastic design vs. traditional linear elastic wind design) could have affected the performance of the LFRS in this building. This scenario highlights a disadvantage to the traditional wind elastic design approach: the structural systems were designed with no knowledge of their inelastic behavior (Tabusso et al., 2016). The results were an "unknown post-yield behavior" and an "undesirable collapse scenario". In addition, the building was subjected to total loss of interior contents; one of the tenants was a cinema theater.

The KIA Diamante Dealership (Fig. 4.3.2) cladding (glass panes, alucobond, and metallic standing seam roof) was destroyed. In addition, components of the secondary steel structures and roof purlins were damaged and all interior contents were lost. The KIA dealership's accessory building with arched roof was subjected to complete wind-induced collapse. Other car dealerships in the area were subjected to similar cladding damage.

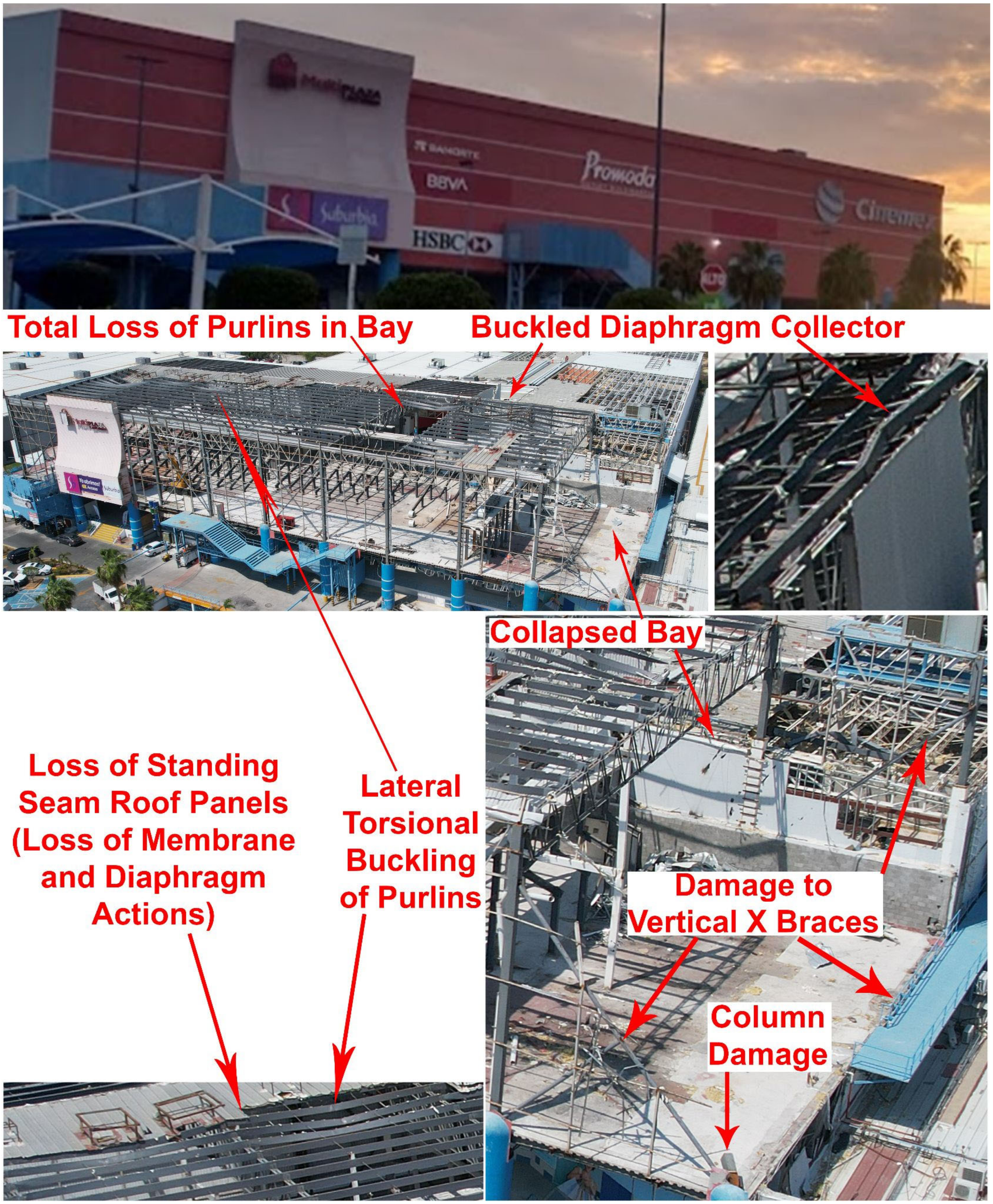
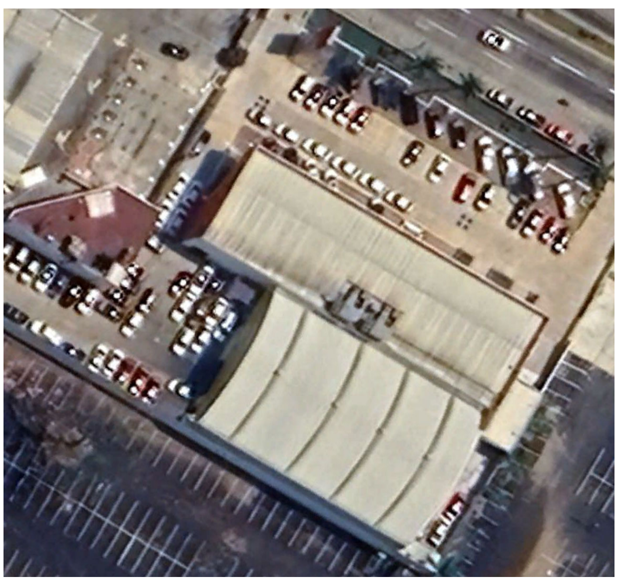


Figure 4.3.1. Damage to Multiplaza las Palmas; (top) before Hurricane Otis (Source: Google Street View); (middle and bottom) after Hurricane Otis (Source: FAST)

(a) (b)



(c) (d)

Figure 4.3.2. Damage to KIA Diamante Dealership: (a) Elevation view pre-Hurricane Otis (Source: Google Street View); (b) Elevation View post-Otis (Source: FAST); (c) Aerial view pre-Hurricane Otis (Source: Google Street View); (d) Aerial view Post-Hurricane Otis (Source: Google Earth)

The Centro Commercial Harbour complex consisted of a reinforced concrete structure with selected structural steel assemblies (e.g., canopies, corridor colonnade) and the large shop front glass façade elements characteristic of retail occupancies. Figure 4.3.3 illustrates destruction of the steel canopies, building contents, glass guardrails, and glass cladding/doors.

Figure 4.3.3. Damage to Centro Commercial Harbour (Source: FAST)

Regular-shaped single-story industrial buildings were severely damaged by Hurricane Otis' winds. The damage includes engineered and non-engineered structures of small businesses and large corporations. Large national (e.g., Bimbo Bread and Grupo Modelo Beer) and international corporations (e.g., Home Depot, WalMart) operate facilities in the region (some in the commercial corridor within Cluster 09). Buildings operated by these corporations are engineered structures designed with recent building code editions. Figures 4.3.4 and 4.3.5 depict roof cladding damage of Grupo Modelo and Bimbo facilities.

Figure 4.3.4. Grupo Modelo in Cayaco (Source: Google Earth)

The Bimbo bread distribution center consists of two warehouses (Fig. 4.3.5). Construction of warehouse 1 on the left concluded approximately in 2015 and construction of warehouse 2 on the right concluded in mid-2023. Warehouse 1 had to be completely reroofed. The buildings don't exhibit any geometric irregularities deviating from the code adopted hypothesis in the wind load quantification procedures.

Figure 4.3.5. Bimbo Distribution Center, including Warehouse 1 on the left and Warehouse 2 on the right (Source: Google Earth).

Home Depot and WalMart wholesale stores (Fig. 4.3.6) were subjected to similar damage as that depicted in Figures 4.3.4 and 4.3.5. In addition, all of the carports in their parking lots collapsed. WalMart is adjacent to Multiplaza las Palmas (on the east), Sam's Club is adjacent to Multiplaza las Palmas (on the west), and Home Depot is located about 100 meters to the west of Sam's Club. Figure 4.3.6 depicts the damage to roof cladding experienced by Home Depot (left) and WalMart (right). Damage to carports in the WalMart parking lot is also shown in this figure. Engineered structures in this area were extensively damaged (Soriana wholesale store was subjected to extensive cladding loss, and the Hyundai and Toyota Diamante dealerships were subjected to similar damage as the KIA Diamante dealership).

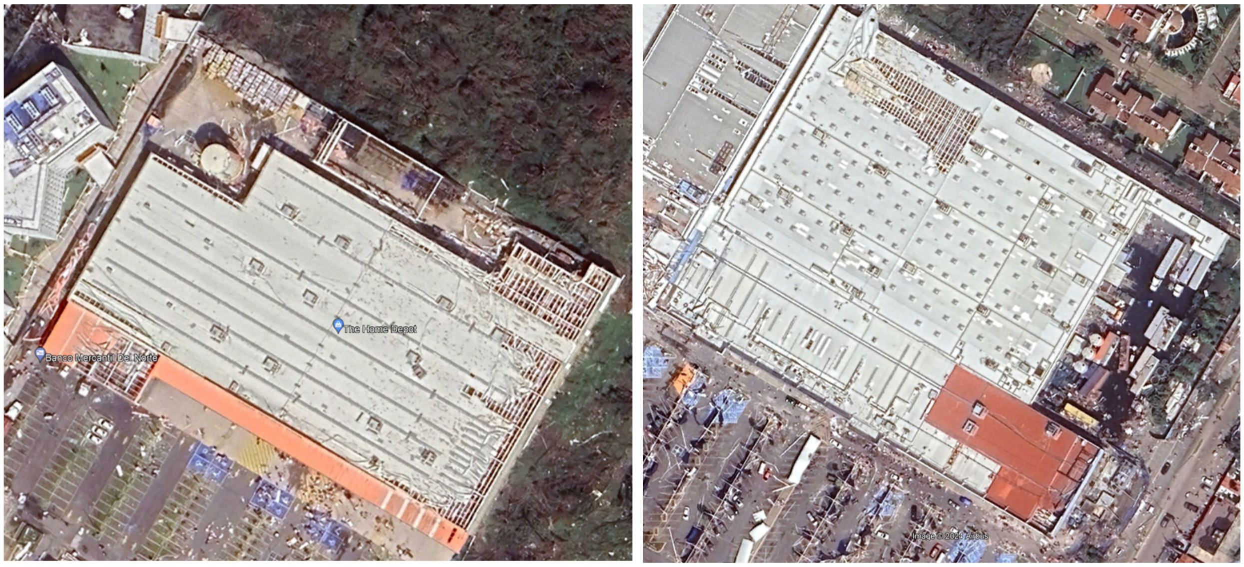


Figure 4.3.6. Damage to Home Depot (left) and WalMart (right) in Cluster 09 (Source: Google Earth).

Low rise commercial and industrial buildings in the Blvd. de las Naciones commercial corridor in Cluster 09, Cluster 02, and Cluster 01 were severely affected. Architectural geometries and enclosure conditions were irrelevant during this storm; most regular and irregularly shaped buildings and enclosed and open buildings equally sustained extensive roof cladding damage, wall cladding damage, and partial or complete collapse. The bluff body aerodynamics of regularly-shaped warehouse buildings has been extensively studied and code prescriptions based on wind tunnel tests of scaled models have been validated via comparisons with numerous full-scale experiments. Nevertheless, a large number of these types of buildings experienced extensive damage. Every low-rise commercial and industrial building that failed during Hurricane Otis in the Acapulco region emphasizes the need to a) update the basic wind velocities prescribed for wind design by incorporating more recent hurricane data to reflect the current weather patterns that had not been previously observed and b) define target yield mechanisms to maintain a ductile sequence of wind-induced damage propagation.

3.4. Other Structures

The FAST team observed damage to other types of structures in the region:

- Tower crane collapses at two construction sites (Fig. 4.4.1)
- Damage to the public lighting infrastructure (Fig. 4.4.2)
- Out-of-plane failure of several free-standing masonry walls[1] (Fig. 4.4.3)
- Extensive collapse of non-engineered timber-framed palapas with palm roofs and billboards (Fig. 4.4.3).

Figure 4.4.1. A tower crane collapsed onto a building under construction (Source: FAST).

Figure 4.4.2. Brittle damage of public lightning poles, including rotation of foundation and out-of-plane base plate bending (Source: FAST).

[1] The team did not prioritize photographs of damaged free-standing masonry walls because their failures were consistent and brittle, due to out-of-plane shear in the tie columns at a region of stress transfer either to a plinth beam at the foundation interface or bond beam in an interface with a supporting element.

Figure 4.4.3. Out-of-plane damage to masonry wall (tie element on top of black column sheared off completely) and damage to a palapas, a non-engineered wood structure with palm thatched roof (Source: FAST).

4. Recommendations for Further Study

Identifying the precise causes of the widespread damage Hurricane Otis inflicted on built infrastructure in Acapulco is premature based on the abbreviated field survey and data collection described in this EARR. Detailed forensic investigations were not the primary objective of this EARR; the objectives were to rapidly capture perishable data and summarize key observations from the field that will enable subsequent specific studies on the causes of the widespread damage. Preliminary estimates suggest that Otis was one of the most powerful cyclones in recorded history, so widespread damage is to be expected. For reference, the peak gusts during landfall of Hurricane Andrew (1992) in Florida were 175 mph and the peak gusts during landfall of Hurricane Otis were 205 mph. Nevertheless, the extensive losses, primarily due to wind damage of engineered structures, motivate preliminary identification of knowledge gaps in the *wind-to-damage* chain and *lateral hazard-to-damage* chain (after incorporating the multi-hazard considerations characteristic of Acapulco). Informed by the recommendations presented in the Preliminary Virtual Reconnaissance Report (PVRR) (Dang et al., 2023) and the information gathered in the field, StEER offers the following updated recommendations for future study:

Topic #1. Elevated Hurricane Risks in a Changing Climate

1. Hurricane Otis made landfall as a powerful Category 5 hurricane in a region of Mexico not historically known for strong hurricanes, and the structural designs and material choices exacerbated the resulting damage. This raises the possibility of similar unexpected cyclone landfalls occurring in other geographic regions, such as San Diego, California, that are also underprepared for strong hurricanes based on existing design wind speed levels, as the climate continues to change. Hurricane risk assessments based on models conditioned upon limited historical data leaves such communities vulnerable and under-prepared. More research is needed on the changes in hurricane risk that can be expected with the changing climate conditions. This should include reviewing wind design standards and preparedness in major cities along the North American Pacific coast such as San Diego, Los Angeles, and Tijuana.
2. The rapid intensification of Hurricane Otis just before landfall joins a growing trend of such cases from recent years. This rapid intensification was not captured by any of the global hurricane models. Improving hurricane models to better capture potential for rapid intensification is a critical need, in addition to improving the communication of such risk to the public and understanding its impacts on evacuation protocols.

Topic #2. Wind Speed-up Effects on Damage within Urban Canopies

1. Physical or computational wind tunnel studies should be performed to study the complex wind flow and wind-structure interaction in the dense urban environments impacted by Otis. These studies should then be validated against the widespread failures of curtain walls and cladding systems in the high-rise buildings that were observed. The architecture of these buildings features complex geometries that deviate from the simple shapes within the scope of most of the procedures adopted by current wind design standards. The damage of building envelope and façade systems using similar construction technologies, which was observed across an array of diverse buildings at multiple stories along their heights, provides a unique opportunity to back-estimate failure wind pressures and validate models.
2. The location of the high-rise buildings downwind of the urban communities of Acapulco elevates the learning opportunities from Hurricane Otis, with applications to a wide range of similarly-positioned (and even denser) urban centers throughout the world, e.g., Miami, Florida. Wind flow through urban canopies remains a topic with significant research gaps.

Topic #3. Wind-Induced Dynamic Response of Buildings and Effects on Lateral Force Resisting Systems (LFRS) and Components and Cladding (C&C)

1. The extensive damage of wall assemblies on the mid- and high-rise buildings of Acapulco motivates evaluation of the validity of the hypotheses inherent in code-adopted methodologies for quantification of wind loads on C&C and LFRS of flexible buildings.
2. Wall assemblies on the flexible buildings of Acapulco were simultaneously subjected to supports excitation and wind-induced pressures (i.e., a system with distributed mass subjected to external forcing functions and excitation of its supports). This scenario deviates from the code adopted assumption that considers wall assemblies statically loaded structures for quantification of wind loads on C&C.
3. Mid- and high-rise buildings in Acapulco have non-negligible participation of higher order modes of vibration and were likely subjected to incursions into their nonlinear behavior range during a 7.1 magnitude earthquake that affected the region in September 7, 2021. Furthermore, some of the buildings were outfitted with seismic damping devices. These conditions deviate from the assumption of *linear elastic response with a single mode of vibration* implicit in the code-adopted methodologies to quantify the dynamic response of the LFRS under wind loads. The dynamic response of the LFRS defines the motion of each story of the building, i.e., it characterizes the excitation of the supports of the wall assemblies of the building envelope.

Topic #4. Wind Design and Retrofit Considerations of Predominantly Seismically-Designed Buildings

1. Failure of wall cladding systems and subsequent damage propagation to interior contents led to complete loss of function in nearly all damaged buildings along the coast of Acapulco. Building envelope systems are excluded from the stringent ductile detailing requirements of the LFRS and were destroyed, rendering most mid- and high-rise buildings inoperable. This observation warrants re-evaluation of code-adopted C&C performance expectations and definition of target yield mechanisms that guarantee a ductile behavior (stable, controlled, and localized damage) in the façade/building enclosure compatible with the objectives of the target yield mechanism of the LFRS. The benefits of expanding the target yield mechanisms to include C&C in defining the wind performance of buildings in sites like Acapulco require further investigation.
2. The observed structural failures and partial collapse of low-rise commercial buildings in the seismic prone region of Acapulco warrant efforts to identify (and address) the multi-hazard design scenarios that could lead to deviations from the code-expected LFRS response (target yield mechanisms). Single-story lightweight steel structures in Acapulco sustained inadmissible wind-induced roof diaphragm (roof bracing) damage and collapse of entire building sections. Further research is necessary to develop design methodologies implementing target yield mechanisms for LFRS under extreme winds that ensure a ductile behavior in seismic prone regions.

Topic #5. Risk Consistency Evaluations of Building Design Provisions for Multi-Hazard Regions

1. The extensive damage to buildings in the Acapulco region warrants an evaluation of the risks of buildings in multi-hazard regions exceeding design limit states implicit in codes and standards. Duthinh and Simiu (2010) and Crosti et al. (2011) emphasized the need for risk consistency for structures in multi-hazard regions and demonstrated that risks of exceeding limit states can be up to twice as high as those for regions where one hazard

dominates. Improving the risk consistency of building code provisions in regions with significant wind and seismic hazards (e.g., Acapulco, Mexico; Charleston, South Carolina; and potentially, San Diego, California) is critical towards effective design of a) preparedness policy and b) strategies for mitigation of hazard-induced damage.

2. Furthermore, the structure prototypes selected for the reliability analyses, strength criteria (e.g., definition of the limit state indicating failure), and the targeted risk differ among prescriptive wind and seismic design methodologies. Resolution of these issues is critical towards ensuring the risks implicit in ASCE 7 minimum requirements are consistent for regions dominated by a single hazard and multi-hazard regions without a clear governing lateral load hazard. The implications of these inconsistencies in the codes should be investigated in light of the damage observed in Acapulco.

Topic #6. Wind and Seismic Design considerations for cladding, curtain wall systems and fenestrations of mid- to high-rise structures

1. Due to the history of strong earthquakes in the state of Guerrero and surrounding regions, the seismic demands on buildings in the region are high. An evaluation of the performance of seismically-governed structures, particularly mid- and high-rise buildings, under the extreme wind speeds produced by Hurricane Otis would be valuable to evaluate the compatibility and discrepancies between seismic- and wind-design philosophies. The design paradigms and goals for wind and seismic design can be in conflict for tall buildings due to the differences in wind and earthquake spectra (Bruneau, 2023). Such a conflict may arise for US-based critical structures built with base isolation or other seismic protection systems; it is unknown how they may perform in the event of extreme wind forces.
2. Related to extreme wind performance and the noted vulnerabilities of cladding systems, it is worthy to investigate whether the glazing used in these buildings would meet the safety requirements for fall protection in the US. Typically, floor-to-ceiling exterior windows have to be laminated so that they do not shatter when broken. The piles of shattered glass observed in videos and images in the wake of Hurricane Otis suggest limited evidence of laminated window glazing (Dang et al., 2023). Thus, forensic investigations to understand the properties of the failed curtain wall systems will not only shed important insights to improve wind-resistance, but could also highlight an area where regulatory reform could improve occupant safety in high-rise hotels and condominiums.

Topic #7. Validating observations of multi-hazard demands

It is rare for a storm of Hurricane Otis' strength to maintain intensity up to landfall and strike densely populated regions. Quantification of the observed damage to various building typologies and occupancies and to critical infrastructure would provide a much-needed dataset that encompasses the high-end of wind risk model predictions. In many such models, the performance of structures under the upper range of the hazard risk curve (e.g., >150 mph) is extrapolated based on models conditioned to observed performance at low and middle ranges of hazard intensity. There is a great need for high quality data under these more extreme wind environments to better condition and calibrate existing risk models. This event presents such an opportunity.

1. It is worthy to investigate whether any buildings instrumented under strong motion networks captured data during the passage of Hurricane Otis. There may have been buildings in Acapulco whose sensors were triggered during the storm. Evaluating the response of such buildings in Otis could improve our understanding of the response of tall buildings to extreme winds.

2. It is paramount that the wind measurements reported during Hurricane Otis be verified. This necessarily includes the 205 mph gust reported by a sonic anemometer in Acapulco under heavy rain conditions, but also includes several other lower wind measurements. While there are some reports of verification by local authorities, details of metadata verification (instrument height, upwind terrain, measurement technology, etc.) are not fully known.

While this event would satisfy the criteria to escalate to a Level 3 response, security issues in the affected area and Level 4 travel advisory from the Department of State prohibits American citizens from traveling or RAPID equipment from deploying. StEER is thankful to the FAST, who are Mexican citizens, for their efforts to at least collect some data through a rapid survey of the region. However, these security risks and travel restrictions will not allow StEER to send a larger team and thus **the response will not escalate to Level 3** with in-depth performance assessments collected by a second FAST. However, StEER does encourage the community's continued engagement on the topics listed above using the data described in this report, other data sources, and any virtual research tools. If the security situation improves sufficiently to permit a Level 3 response before forensic data is completely lost, StEER will make announcements through its regular channels. Meanwhile, the data collected in this Level 2 response will be quality controlled and released on DesignSafe under project PRJ-4231 for further re-use by the community.

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Appendix: Photo Metadata

Table A.1. Appendix: Metadata for Photos Included in Section 4

Figure ID	Latitude	Longitude	Source of Photo
3.1	NA	NA	Google Earth and NHC (track updated on April 2024)
3.2	NA	NA	Fulcrum App
3.3	NA	NA	Google Earth
4.1.1	NA	NA	FAST
4.1.2	NA	NA	FAST
4.1.3	NA	NA	Google Earth
4.1.4	16.782524	-99.805808	Google Earth
4.1.5	16.782524	-99.805808	Google Street View and FAST
4.1.6	16.782524	-99.805808	Google Maps and FAST
4.1.7	16.782524	-99.805808	Google Maps and FAST
4.1.8	16.78513121	-99.80962584	Google Street View, Google Maps, and FAST
4.1.9	16.77541054	-99.79620659	FAST
4.1.10	16.77294523	-99.79117488	maroadiamante.mx/, Google Street View, and FAST
4.1.11	16.78443692	-99.80857827	FAST
4.1.12	16.77515651	-99.79027035	Google Maps and FAST
4.1.13	16.78280219	-99.80630212	Google Maps and FAST
4.1.14	16.7852109	-99.80709267	FAST
4.2.1	16.71635599	-99.70505475	FAST
4.2.2	16.74992889	-99.76239264	Google Maps and FAST (Fulcrum)
4.2.3 Top	16.753652	-99.766644	FAST
4.2.3 Bottom	16.754894	-99.768924	FAST
4.3.1	16.79738708	-99.81042181	Google Maps and FAST
4.3.2	16.80129901	-99.82189578	Google Street View, Google Earth, and FAST
4.3.3	16.77117157	-99.77802389	FAST
4.3.4	16.83130349	-99.81207277	Google Earth
4.3.5	16.76777673	-99.76503533	Google Earth
4.3.6 Left	16.79915549	-99.81292192	Google Earth
4.3.6 Right	16.79737272	-99.80926831	Google Earth
4.4.1	16.73874071	-99.74723287	FAST
4.4.2	16.76339773	-99.75546007	FAST
4.4.3	16.77480082	-99.7960028	FAST