Hurricane Laura Damage Survey

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1. INTRODUCTION

On August 27, 2020, Hurricane Laura struck southwest Louisiana and extreme southeast Texas. The author experienced the hurricane firsthand in Lake Charles, LA, then spent three days conducting a damage survey. The primary purpose of the damage survey was to evaluate the performance of various structures that experienced strong winds. Refer to Figure 1.

Utilizing degrees of damage (DoD) descriptions in the Enhanced Fujita (EF) scale, the author estimated failure wind speeds. See Wind Science and Engineering Center (WSEC 2006). Many structures sustained severe wind damage or failed when three-second wind gusts reached 40-58 m/s (90-130 mph). In most cases, building failures occurred quickly, with wind duration not being a factor. Therefore, the EF-scale, typically used for tornado events, was deemed appropriate for these damaged buildings. Where catastrophic failures occurred, weaknesses in connections were factors in the failures. Many buildings experienced severe damage when windward windows or doors failed allowing wind to enter the buildings creating additional upward forces on roofs and increased outward forces on leeward walls. Corrosion of steel anchors in the salt air environment was common and contributed to failures of certain structural components.

Most buildings survived the strong winds when their structural elements provided continuous load paths from roofs to foundations. The absence of structural damage to such buildings proved it was possible to survive a major hurricane. One success story was cantilevered steel poles that supported traffic signals and vaned in the wind, rotating on slip plates secured to their pedestals. In strong winds, these poles simply vaned downwind thereby saving them from severe damage.

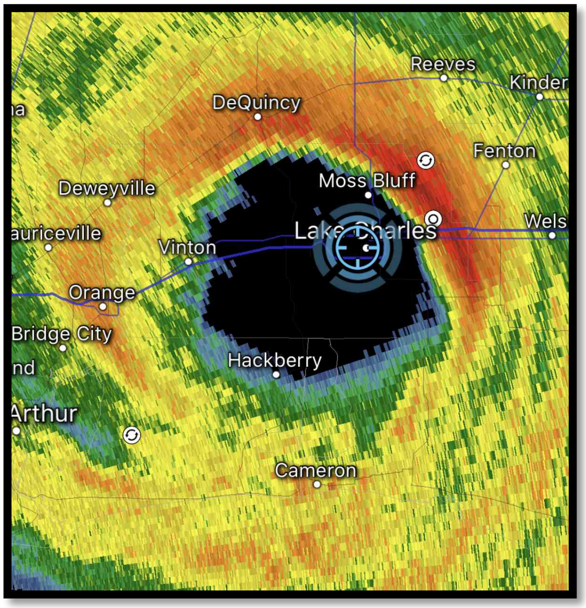

Figure 1. The eye of Hurricane Laura over Lake Charles, LA around 0730 UTC. The author was on top of a parking garage within the blue circle. Image from RadarScope.

2. STORM TRACK

Hurricane Laura made landfall at Cameron, LA around 0600 UTC on August 27, 2020. According to the National Weather Service (NWS 2020), Laura was the strongest hurricane to strike southwest Louisiana since record keeping began in 1851. The hurricane moved due north toward Lake Charles at about 4.5 m/s (10 mph), weakening slowly. The highest wind speed recorded by the NWS in Lake Charles was a five-second wind gust of 116 kt (133 mph) out of the east at 0732 UTC before the wind equipment failed. The Florida Coastal Monitoring Program (FCMP) erected a portable tower at Chennault International Airport on the east side of Lake Charles and recorded continuously with peak three-second wind gust of 115 kt (132 mph) out the east at 10 m (33 ft). A second FCMP site in Sulphur, LA recorded a peak three-second wind gust of 96 kt (110 mph) from the east on another 10 m (33 ft) tower.

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3. DAMAGE SURVEY

The author spent three days surveying damage in and around Lake Charles, LA after experiencing the full wrath of the hurricane from the top story of a parking garage at St. Patrick's Hospital in the center of Lake Charles, LA. The primary purpose of the damage survey was to study the performance of various building types and document the degrees of damage before cleanup began. Another purpose was to provide additional photographic images of building performance to the EF-scale database. A third purpose was to provide input regarding building performance to the next generation of the Enhanced Fujita (EF) scale currently being developed as a standard by the American Society of Civil Engineers (ASCE). The author serves on this committee.

The EF-scale was adapted from the original Fujita (1971) or F-scale. The NWS has employed the EF-scale since 2007 to rate degrees of damage (DoDs) to buildings and to estimate failure wind speeds. The DoDs were selected for various Damage Indicators (DIs) which included different building types and other items such as poles and trees. While the EF-scale has been used primarily for rating tornado damage, it can be applied to rating hurricane damage if failures occur quickly when load duration is not an issue. Marshall (2006) utilized the EF-scale in his survey of Hurricane Katrina damage. According to the Hurricane Research Division (2018), Fujita employed his F-scale for several hurricanes including Alicia (1983), Diana (1984), Elena (1985), Hugo (1989), Andrew (1992), and Iniki (1992).

3.1 Residences (DI 2)

There was widespread wind damage to residences in the Lake Charles area, particularly to roof coverings. In some cases, residences experienced structural damage when toenailed roof structures failed. Broken windows or doors on the windward sides of buildings increased internal wind pressures to help lift poorly attached roofs from the walls. In addition, trees fell on many residences damaging them.

Frequently observed problems were improper attachment of roof coverings, especially when asphalt shingles were nailed too high above the sealant strips. In addition, overdriven fasteners tore through the shingles. Typically, there were four nails per shingle instead of the six nails required for hurricane prone areas.

The combination of high nailing, overdriven fasteners, and fewer fasteners than required resulted in less than half the required number of fasteners in the shingles to resist wind uplift. The result was widespread wind damage to asphalt shingle roofs, particularly on windward slopes. Wind damage included flipped, creased, torn, and removed shingles. Asphalt shingle roofs that were nailed correctly sustained far less wind damage than those roofs where shingles were not installed correctly. Loss of roof coverings and underlayment allowed water ingress which greatly increased the amount of interior damage to residences. Refer to Figure 2.

Vinyl siding also performed poorly in strong winds. The author observed torn hem lines along the tops of vinyl siding panels with nails remaining intact in the underlying sheathing. Properly installed vinyl siding was loose hung with bottom rows interlocked to the lower panels. However, since the siding panels were flexible, they unlocked in the turbulent winds. Consideration should be given to restricting installation of vinyl siding in hurricane prone areas. Homes clad with hardboard siding outperformed those with vinyl siding.

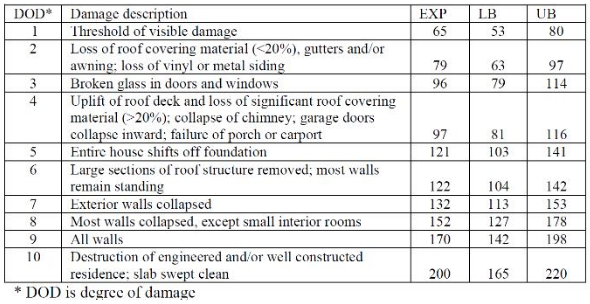
The vast majority of residences had DoDs of 4 or less on the EF-scale, with damage limited to roof coverings and cladding items. A small percentage of homes experienced damage where they had windward windows or garage doors fail allowing internal pressures to help lift and remove the roofs (DoD 6). Refer to Figure 3. Expected failure wind speeds for DoD 4 damage is around 43 m/s (97 mph) whereas, expected failure wind speeds for DoD 6 is around 55 m/s (122 mph). Thus, we found the wind speeds listed in the EF-scale agreed well with the residential DoDs and locally measured wind speeds. See Table 1.

Where roof failures occurred, there was no evidence of metal straps or clips used to attach rafters to wall top plates. Roof failures initiated where rafters were toenailed to wall top plates. Nails were simply pulled out of the wood. Marshall (1983) has shown that toenailed connections are inherently weak against uplift. Tension pull tests on 30, 16d toenailed connections had an average pull-out strength of 1325 N (298 lbs.). There is no doubt that properly installed steel straps would have prevented such roof failures. Pull-out strength of rafter/wall top plate connections secured with steel straps can exceed 5000 N (1124 lbs.).

Figure 2. Wind damage to asphalt shingle roof coverings on residences. The inset image shows high nailing (yellow circles) with nails missing top laps in the overlying shingles (red circles).

Figure 3. House in Vinton, LA which lost its entire roof. The front side of house faced north and was windward to the strongest winds. Failure of the front doors and windows allowed internal pressure to help lift the roof. Inset image (A) shows upside down roof in the back yard with “birdsmouth” cut outs in rafters (yellow box) and close-up of broken toenailed connection (B) where two parallel rust stains indicate where angled nails had been.

Table 1. DoDs for residences.



DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	53	80
2	Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding	79	63	97
3	Broken glass in doors and windows	96	79	114
4	Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward; failure of porch or carport	97	81	116
5	Entire house shifts off foundation	121	103	141
6	Large sections of roof structure removed; most walls remain standing	122	104	142
7	Exterior walls collapsed	132	113	153
8	Most walls collapsed, except small interior rooms	152	127	178
9	All walls	170	142	198
10	Destruction of engineered and/or well constructed residence; slab swept clean	200	165	220

* DOD is degree of damage

3.2 Manufactured Homes (DI 3)

The author examined hundreds of manufactured homes during the damage survey including those in the Oakhurst Mobile Estates on the east side of Lake Charles which contained 256 single-wide homes. Most manufactured homes had both frame ties and over-the-top ties. All 256 homes remained intact on their foundations with no structural damage despite 59 m/s (132 mph) winds recorded at the FCMP tower at nearby Chennault International Airport. However, in many instances, galvanized steel straps were slack, apparently due to rocking movements of the manufactured homes in the wind. These straps will need to be re-tightened. Typical wind damage to manufactured homes included loss of skirting, vinyl siding, and asphalt roof shingles. Proper anchoring of manufactured homes proved they can survive major hurricanes. Refer to Figure 4.

Figure 4. Damage to a newer manufactured home with over-the-top and frame ties included loss of skirting, siding, and roofing. The inset image shows slackened ties, apparently due to rocking movement of the home during the hurricane.

A total of 94 single-wide homes were examined at the Tommasi Mobile Village where the vast majority of homes only had frame ties. Eight homes were destroyed, with complete separation of the wood boxes from the floors; the anchored undercarriages remained in place. Close examination indicated that wall studs were stapled and screwed to wall bottom plates. In 3 of the 8 instances, termites had consumed the wall bottom plates, leaving wall studs hanging from their top plates. In all failed houses, no steel straps were observed between wall studs and the bottom plates or between the roof structure. Destruction of the 8 manufactured homes was consistent with DoD 6 with expected failure wind speeds around 47 m/s (105 mph). Refer to Figure 5 and Table 2.

Figure 5. Separation of the wood box from the floor in this manufactured home. Inset image shows wall studs were secured to wall bottom plates with staples and screws, not steel straps as done today.

South of Sulphur, LA, there were five manufactured homes which rolled off their concrete block supports. Close inspection revealed all homes had frame anchors, but the steel straps were severely corroded and had broken. Refer to Figure 6. All five manufactured homes were oriented north-south, so they were perpendicular to the strongest hurricane winds from the east. Damage to these units was consistent with DoD 5 for manufactured homes with expected failure wind speeds around 44 m/s (98 mph).

Figure 6. Rolled manufactured home. The inset image shows a severely corroded and broken steel strap, along with corroded anchor head and stabilizer plate.

Table 2. DoDs for manufactured homes.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	61	51	76
2	Loss of shingles or partial uplift of one-piece metal roof covering	74	61	92
3	Unit slides off block piers but remains upright	87	72	103
4	Complete uplift of roof; most walls remain standing	89	73	112
5	Unit rolls on its side or upside down; remains essentially intact	98	84	114
6	Destruction of roof and walls leaving floor and undercarriage in place	105	87	123
7	Unit rolls or vaults; roof and walls separate from floor and undercarriage	109	96	128
8	Undercarriage separates from unit; rolls, tumbles and is badly bent	118	101	136
9	Complete destruction of unit; debris blown away	127	110	148

DOD is degree of damage

3.3 Apartments (DI 5)

The author conducted detailed examinations of three apartment complexes in Lake Charles. Fairview Crossing consisted of 23 two-story, wood-framed apartment buildings and a one-story, wood-framed office building. Each apartment building, including the office, sustained damage to their east gable ends, including immediate portions of the roof structure. Winds pushed the east-facing gable ends inward and wind entered the attic spaces. Most roof coverings were removed. This level of damage was consistent with DoD 3 in the EF-scale and had an expected failure wind speed of 55 m/s (124 mph). Refer to Figure 7 and Table 3.

Figure 7. Failure of east facing gable ends on buildings at Fairview Crossing apartments.

Damage to The Orleans and Bancroft Street Apartments consisted of complete removal of the roof structures. The Orleans apartment building had covered walkways that faced east and south, facing the strongest winds. Both apartment buildings had window glass failures on windward elevations. These window failures resulted in increased internal wind pressures which aided in uplifting these roofs. Rafters were toenailed (not strapped) to wall top plates, and these connections pulled loose as the roofs lifted, leading to their complete removal. Refer to Figures 8 and 9. This level of damage was consistent with DoD 4 in the EF-scale with an expected failure wind speed of 62 m/s (138 mph). However, due to inherent deficiencies, failure wind speeds (covered walkway facing the wind with interior wind pressure contributions) were closer to the lower bound of 54 m/s (120 mph).

Figure 8. Loss of the roof structure with an east-facing walkway overhang. Additional lift occurred due to the overhang and to internal pressurization due to broken windows.

Figure 9. Lost brick masonry on south and east walls along with roof removal on an apartment building on Bancroft Street. The car remained in place.

Table 3. DoDs for apartment buildings.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	76	63	95
2	Loss of roof covering (<20%)	99	82	121
3	Uplift of roof decking; significant loss of roof covering (>20%)	124	107	146
4	Uplift or collapse of roof structure leaving most walls standing	138	120	158
5	Most top story walls collapsed	158	138	184
6	Almost total destruction of top two stories	180	155	205

* DOD is degree of damage

3.4 Motels (DI 5)

The author evaluated damage to several motels in Lake Charles including a cluster of 8 buildings on West Prien Lake Road near Holly Hill Road. Seven of the eight motels had light to moderate cladding damage including loss of roof coverings, some greater than 20 percent, along with removal of hardboard siding, and exterior insulation and finish systems (EIFS). This level of damage was consistent with DoD 4 on the EF-scale and expected failure wind speeds of 42 m/s (95 mph). Refer to Table 4.

EIFS siding failed on a La Quinta in north Lake Charles along Sampson Street when bead board insulation wall panels pulled off the oriented strand board (OSB) sheathing. EIFS panels were secured to OSB sheathing with screws and plastic disks installed every 30 cm (12 inches). Failure of the EIFS left cone-shaped remnants of the bead board insulation beneath the disks which remained clamped to the OSB sheathing. Refer to Figure 10.

Figure 10. Loss of EIFS cladding from the motel. EIFS panels were secured to OSB sheathing with screws and plastic disks. Inset A shows the cone-shaped area of bead board insulation that remained attached to the walls beneath the fastener plate. Inset B shows the back side of the EIFS panel lying on the ground with holes at attachment points.

The most severe wind damage in this group of 8 motel buildings occurred to a Motel 6 where a portion of the roof structure was removed at the east end of the building. Close examination revealed wood roof trusses were toenailed to wall top plates and walls were straight nailed to bottom plates (no metal straps). Toenailed connections between the trusses and wall top plates pulled apart leading to removal of the roof. North and south walls were no longer supported by the roof at the top and pivoted to the north as straight-nailed wall bottom plates pulled out of the concrete. This level of damage was consistent with DoD 6 on the EF-scale with expected with failure wind speeds of 55 m/s (123 mph). Refer to Figure 11.

Figure 11. Removal of the roof structure at the east end of the Motel 6. Damage included toppling of top story walls. Inset A shows failed wall bottom plate connections. Inset B shows toppling of the north wall.

Table 4. DoDs for motels.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	66	54	83
2	Loss of roof covering (<20%)	80	67	99
3	Broken windows or patio doors	89	74	107
4	Uplift of roof decking; significant loss of roof covering (>20%);loss of EIFS wall cladding	95	80	116
5	Uplift or collapse of canopy over driveway	99	81	118
6	Uplift or collapse of roof structure leaving most walls standing	123	103	143
7	Collapse of top story exterior walls	138	121	156
8	Collapse of most top story walls	143	127	162
9	Collapse of top two floors of three or more stories	170	144	185
10	Total destruction of entire building	190	163	217

* DOD is degree of damage

3.5 Small retail building (DI 8)

Several small retail buildings sustained catastrophic failures, and two examples are presented here. The Auto Zone store on Nelson Street in Lake Charles had concrete masonry unit (CMU) perimeter walls. A large, store-front metal framed window unit was anchored with screws into grouted cells in the CMU knee wall. Steel roof trusses were anchored to bond beams at the tops of the masonry walls and open web steel joists were welded perpendicular to the trusses. Failure of the window frames from strong east winds led to internal pressurization of the building which helped lift the entire roof structure off the walls. The roof became airborne landing upside down in the back yard of a residence to the west. Refer to Figures 12 and 13. Damage to this building was consistent with DoD 6 for small retail buildings with expected failure wind speeds of 53 m/s (119 mph). Refer to Table 5.

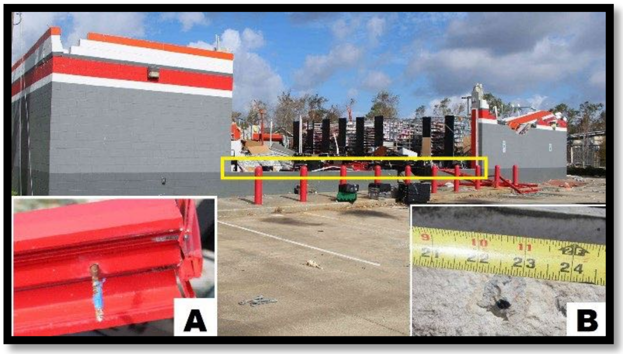


Figure 12. Catastrophic failure of the Auto Zone building occurred when windward window frames blew inward resulting in internal pressurization and removal of the entire roof. The yellow box shows the failure location. Insert A shows where a screw, securing the window frame, simply pulled out of the grouted cell. Insert B shows the small divot in the grouted CMU cell where the screw had attached the window frame.

Figure 13. Aerial image showing complete removal and flipping of the Auto Zone roof into a neighboring back yard due to internal pressure effects after front window failure. Note the lack of damage to the house. Source: Google.

The convenience store at 5th Avenue and Prejean Drive in Lake Charles was a wood-framed structure with exterior insulation and finish system exterior (EIFS). The roof was constructed with wood trusses covered with metal panels. Failure of the front east wall frame occurred when cut nails, which attached the wall bottom plates, pulled out of the concrete foundation. This resulted in the wall being pushed inward and allowed wind to pressurize the building. The roof structure lifted and collapsed due in part to internal wind pressure. The metal roof was folded back from the front. Cut nails never should have been used to attach exterior wall plates to the foundation and was the weak point in this wall system. The author deemed this type of construction to have lower than typical wind resistance and assigned a failure wind speed of 45 m/s (101 mph) in DoD 6 for small retail buildings. In contrast, the steel canopy over the gas pumps sustained only minor fascia damage and no structural damage. Refer to Figure 14.

Figure 14. Failure of front (east) wall at this convenience store when the wood frame wall, attached with cut nails. The red box in this image shows where the wall failure initiated. Inset A shows a cut nail protruding from the bottom side of the wall plate. Inset B shows the divot in the concrete slab where the cut nail had been installed.

Table 5. DoDs for small retail buildings.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	54	81
2	Loss of roof covering (<20%)	78	65	98
3	Broken glass in windows and doors	86	72	103
4	Uplift of roof decking; significant loss of roof covering (>20%)	98	81	119
5	Canopies or covered walkways destroyed	98	83	114
6	Uplift or collapse of entire roof structure	119	101	140
7	Collapse of exterior walls; closely spaced interior walls remain standing	138	120	159
8	Total destruction of entire building	167	143	193

* DOD is degree of damage

3.6 Strip Mall (DI 10)

Many strip malls sustained damage during the hurricane. Most of the damage to strip malls involved failure of large window units or cladding on windward sides of the buildings as well as loss of roof coverings. Structural damage to a strip mall at Ryan Street and West Sale Road in Lake Charles involved the east CMU wall toppling into the building. This failure caused the open web steel joists, which supported the roof, to collapse. Wall and foundation rebar were present in ungrouted cells. Foundation rebar extended 10 inches above the concrete slab while wall rebar extended up to 20 inches below the concrete slab. Depth of the rebar became visible when the wall failed. This degree of damage was between DoD 4 and 7 in the strip mall DI indicating a median failure wind speed of around 49 m/s (110 mph). Refer to Figure 15 and Table 6.

Figure 15. Collapse of the east-facing loadbearing wall on a strip mall. Inset image shows wall and foundation rebar at the base of toppled wall.

Table 6. DoDs for strip malls.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	54	81
2	Uplift of roof covering at eaves and roof corners	80	66	100
3	Broken windows or glass doors	88	72	105
4	Uplift of roof decking	101	84	122
5	Collapsed façade or parapet walls	103	85	125
6	Covered walkways uplifted or collapsed	103	86	125
7	Uplift or collapse of entire roof structure	122	103	143
8	Collapse of exterior walls; closely spaced interior walls remain standing	140	117	165
9	Complete destruction of all or a large section of building	171	147	198

* DOD is degree of damage

3.7 Low Rise Building (DI 17)

The author inspected several church buildings in Lake Charles classified as low-rise buildings in the EF-scale. Most churches sustained damage to steeples, wall cladding and roof coverings. There was a significant wall failure to the sanctuary of the Glad Tidings church at the intersection of East College and Texas Street. This two-story, steel-framed structure had perimeter steel stud walls enclosed with brick masonry. Steel studs were nailed into steel I-beams. The nails extended only 1.3 cm (1/2 inch) into the steel. This wall attachment had little lateral resistance and the connections failed at the bases of the walls. Strong winds pushed the northeast wall inward and the southeast wall outward. Some wind damage occurred to the roof covering. The sanctuary structure remained intact. Applying the low-rise building DI in the EF-scale, DoD 3 would be closest to describing this damage, but failure wind speeds were determined to be at the lower bound of 37 m/s (83 mph). Refer to Figure 16 and Table 7.

Figure 16. East side of the Glad Tidings church building showing second story wall failures. Cold formed steel bottom plates were nailed into the underlying steel I-beams and simply pulled out of the steel (yellow boxes). The inset image is a close-up view of a protruding nail in the upside-down wall bottom plate.

Table 7. DoDs for low rise buildings.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	68	55	83
2	Loss of roof covering (<20%)	80	67	103
3	Uplift of metal roof decking at eaves and roof corners: significant loss of roofing material (>20%)	101	83	120
4	Broken glass in windows, entryways or atriums	101	83	122
5	Uplift of lightweight roof structure	133	114	157
6	Significant damage to exterior walls and some interior walls	143	122	167
7	Complete destruction of all or a large section of building	188	161	221

* DOD is degree of damage

3.8 High Rise Building (DI 19)

The Capital One Tower in downtown Lake Charles is the tallest building in the city with the rooftop elevation being around 95.7 m (314 ft). This 22-story, glass clad, steel-framed structure, built in 1981, had experienced several hurricanes. Storm chaser video taken from the adjacent parking garage during Laura showed glass breakage began in the northern eyewall and quickly escalated. Glass failure was attributed to the combination of glass type, wind pressure, flying/falling debris, and perhaps design/installation issues. Glass breakage was much less severe during Hurricane Rita in 2005. Peak wind gusts during Rita were around 49 m/s (109 mph) in Lake Charles, providing a good point of reference as to the wind speeds necessary to initiate damage. The level of damage in Rita was consistent with DoD 4 in the EF-scale with expected failure wind speeds of 45 m/s (101 mph). However, winds during Laura were stronger, resulting in more damage. In this case, wind duration caused cascading failures of windows breakage, as broken glass shards struck and broke additional windows. Refer to Figure 17 and Table 8.

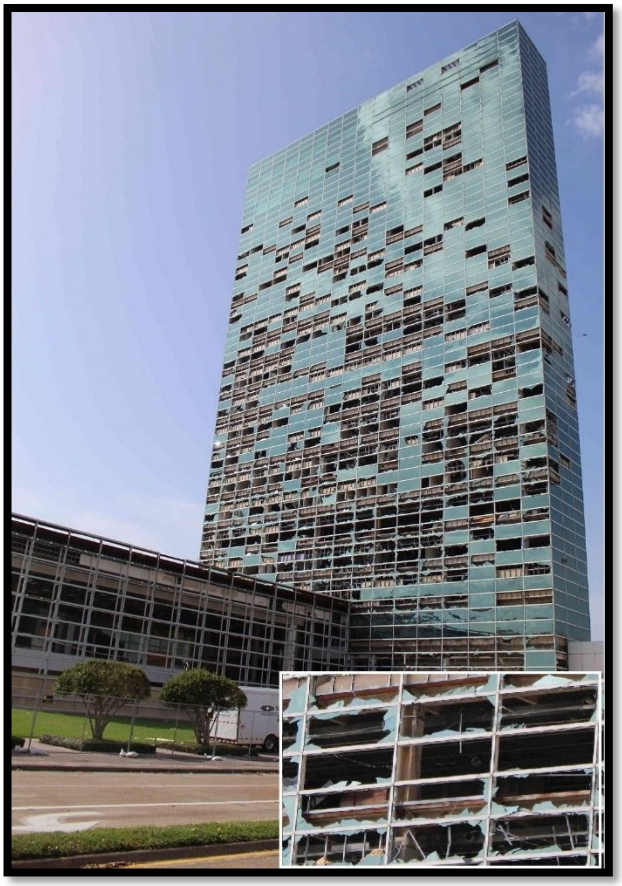


Figure 17. Extensive glass breakage on a high rise in downtown Lake Charles.

Table 8. DoDs for high rise buildings.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	70	58	86
2	Loss of roof covering (<20%)	86	69	107
3	Damage to penthouse roof and walls; loss of rooftop HVAC equipment	93	75	111
4	Broken glass in exterior walls at 1st and 2nd floors; broken glass in entryways	101	83	120
5	Damage to parapet walls or coping	104	87	122
6	Broken curtain wall panel anchors	129	110	157
7	Significant loss of roofing material (>20%)	143	115	165
8	Significant damage to curtain walls and interior walls	145	123	172
9	Uplift or collapse of roof structure	159	123	183
10	Permanent structural deformation	228	190	290

3.9 Metal Building System (DI 21)

The author inspected more than a dozen metal building systems (MBS) from Vinton to Sulphur to Lake Charles, LA. The most common damage was to roll up door systems. Failures of roll up doors on building windward sides led to building pressurization unless leeward side doors also failed. Where opposing doors failed, there was little or no structural damage to the steel framing or cladding. Roll up door failures on opposite sides of buildings prevented internal pressure build-up. Failures of roll up doors are listed as DoD 2 on the EF-scale with expected failure wind speeds of 40 m/s (89 mph). Refer to Figure 18 and Table 9.

Five metal building systems (MBS) at the Calcasieu Industrial Park in Sulphur, LA, sustained various degrees of damage ranging from damage to roll up doors to complete building collapse. One building in this Industrial Park sustained complete failure of the windward (east) end wall. Close examination revealed shot pins were fastened to cold formed steel bottom wall plates into the concrete foundation. End wall failure occurred when the shot pins securing the east wall bottom plate pulled out of the slab, leaving spalled spots of concrete at 76 cm (30 in) intervals. Removal of roof and wall cladding was limited to the easternmost bay. This level of damage was consistent with DoD 3 and expected failure wind speeds of 42 m/s (95 mph). Refer to Figure 19.

A collapsed metal building in Vinton, LA experienced peak wind gusts of around 45 m/s (100 mph) out of the north. The north end wall blew in, and the south end wall blew out, and the center of the building collapsed. Plastic hinges developed in beams adjacent to stiffened beam-column connections, and the columns rotated inward. This building collapsed during winds far below expected failure wind speeds of 70 m/s (155 mph) as listed in the EF-scale. It was suspected that the building design/construction did not conform to ASCE 7 wind loads. Refer to Figure 20.

Table 9. DoDs for metal building systems.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	67	54	83
2	Inward or outward collapsed of overhead doors	89	75	108
3	Metal roof or wall panels pulled from the building	95	78	120
4	Column anchorage failed	117	96	135
5	Buckling of roof purlins	118	95	138
6	Failure of X-braces in the lateral load resisting system	138	118	158
7	Progressive collapse of rigid frames	143	120	168
8	Total destruction of building	155	132	178

* DOD is degree of damage

Figure 18. Failure of overhead doors on the windward (east) side of this metal building resulted in outward failure of the north side door. The building frame and cladding remained undamaged. The inset image is a closer view of the failed doors.

Figure 19. End wall failure on the windward side of this metal building system. The cold formed steel base plate was shot pinned to the concrete foundation and was a connection too weak to resist lateral wind loads.

Figure 20. Collapse of a metal building system in Vinton, LA. The north wall blew in, and south wall blew out. The inset image shows plastic hinges developed on the beam (rafter) side of the stiffened beam-column connection.

3.10 Service Station Canopy (DI 22)

Damage to service station canopies usually involved removal of cladding and roof panels. However, several canopies toppled in the strong winds. Single column line canopies were prone to tipping over. Plastic hinges formed at the bases of the columns. According to the EF-scale, this level of damage (DoD 4) was consistent with expected failure wind speeds of 49 m/s (109 mph), about ten percent higher than the peak winds experienced at this location based on the level of the surrounding damage. Refer to Figure 21 and Table 10.

Figure 21. Toppled single column canopy in Vinton, La from strong north winds. The inset image shows plastic hinge formation at the base of the tubular steel column.

Table 10. DoDs for service station canopies.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	63	45	79
2	Fascia material blown from canopy	78	64	96
3	Metal roof panels stripped from canopy	92	74	113
4	Columns bend or buckle under wind load	109	88	135
5	Canopy collapsed due to column foundation failure	114	90	144
6	Complete destruction of canopy	133	110	163

*Degree of Damage

3.11 Electrical Transmission Lines (DI 24)

There was widespread damage to electrical transmission lines during Hurricane Laura. It did not matter whether poles were wood, concrete, or steel. All pole types failed, failing mostly at their bases. Refer to Figure 22. According to the EF-scale, toppling of wood poles (DoD 4) has an expected failure wind speed of 53 m/s (118 mph). Refer to Table 11. However, toppling of steel and concrete poles (DoD 5) listed in the EF-scale has an expected failure wind speed of 62 m/s (138 mph). The author believed these failure wind speeds were about ten to twenty percent higher than necessary to fail these poles.

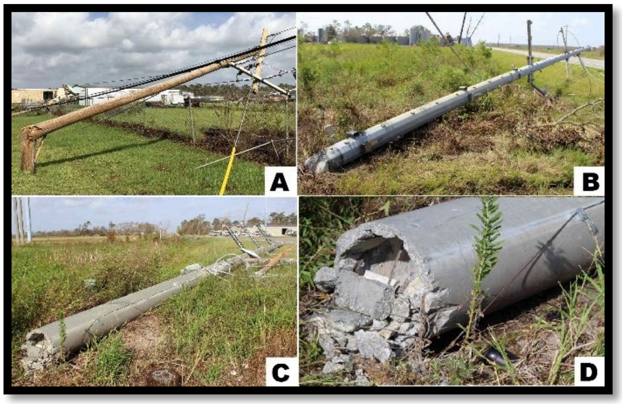


Figure 22. Broken poles: A) wood, B) steel, and C) concrete with D) showing a close-up view of a failed concrete pole at ground level.

Table 11. DoDs for electrical transmission systems.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	83	70	98
2	Broken wood cross member	99	80	114
3	Wood poles leaning	108	85	130
4	Broken wood poles	118	98	142
5	Broken or bent steel or concrete poles	138	115	149
6	Collapsed metal truss towers	141	116	165

* DOD is degree of damage

3.12 *Free Standing Towers (DI 25)*

Several free-standing towers toppled during the hurricane. The KPLC television tower buckled near mid-height with the top portion of the four-legged steel tower falling through the television studio roof. Refer to Figure 23. The tower was approximately 91 m (300 ft) tall and constructed with a bolted assembly of structural steel angle sections. Tower legs were anchored to steel-reinforced concrete piers. Google Street View images taken before the storm showed large antennas mounted to the top of the tower. These antennas increased wind loading on the tower. An adjacent four-legged communications tower (to the north) remained erect. Refer to Table 12.

The three-legged steel tower at KSWL fell northwest, striking two adjacent buildings. Tower legs were solid steel sections that tapered in width with increasing height above the ground. Refer to Figures 24 and 25. In the EF-scale document, collapse of a microwave tower is listed as DoD 3 with an expected failure wind speed of 61 m/s (136 mph), a number slightly higher than the peak winds measured during the hurricane.

Figure 23. Collapsed four-legged tower at KPLC TV in Lake Charles.

Figure 24. Toppled three-legged tower at KSWL TV in Lake Charles. The inset image is a closer view of the base of the bent leg, inside the yellow circle in the main image.

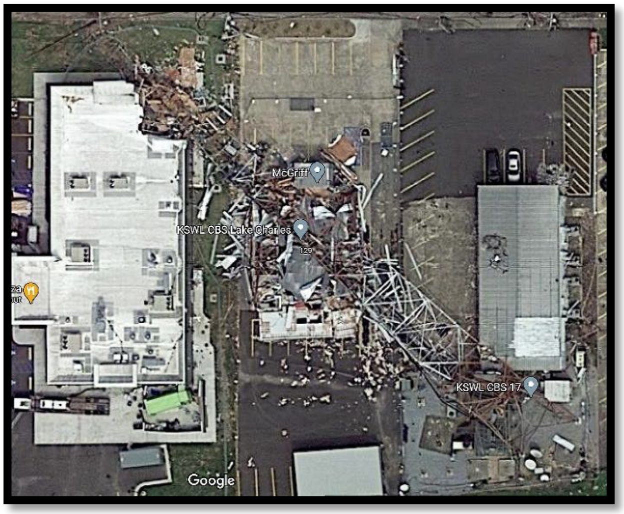
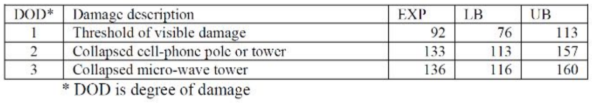


Figure 25. Aerial image showing the KSWL TV tower which fell northwest striking two adjacent buildings. Source: Google.

Table 12. DoDs for free-standing towers.



DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	92	76	113
2	Collapsed cell-phone pole or tower	133	113	157
3	Collapsed micro-wave tower	136	116	160

* DOD is degree of damage

3.13 *Free Standing Light Poles (DI 26)*

The author examined dozens of toppled free-standing light poles during the damage survey. These poles were round or hexagonal hollow steel sections that tapered to smaller widths with increasing height above the ground. Two steel light poles toppled at the Sulphur High School stadium. These 30 m (100 ft) tall poles supported light arrays at their tops. Pole bases were embedded into concrete piers. All light poles buckled at their bases falling southwest. Refer to Figure 26. According to the EF-scale, toppling of such poles (DoD 3) would yield expected failure wind speeds of 53 m/s (118 mph). However, given the large array of lights at the tops of the poles and presence of corrosion at pole bases, the expected failure wind speeds probably were closer to the lower bound of DoD 3, or near 45 m/s (99 mph). Refer to Table 13. By comparison, the FCMP tower in Sulphur, LA recorded a peak gust of 49 m/s (110 mph).

Figure 26. Toppled tapered steel light poles at the high school stadium in Sulphur, LA. Poles buckled at their bases then bent again when hitting the stands (inset A). Close examination of the pole bases revealed corrosion (inset B).

Table 13. DoDs for free-standing poles.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	81	67	100
2	Bent pole	102	85	120
3	Collapsed pole	118	99	138

* DOD is degree of damage

One universal success story was the many cantilevered steel poles with luminaries (traffic signals) designed to vane in the wind. These poles had slip plates securing their pedestals. In strong winds, these poles simply pivoted downwind, thereby saving them from severe damage. However, one cantilevered pole did fail. Close examination revealed the slip plates were not tightened sufficiently, causing the pedestal and cantilevered pole assembly to topple. Refer to Figure 27.

Figure 27. Light poles vaned in the wind, pivoting about their bases (A). Failure of one pole exposed the slip plates which allowed the pole/pedestal to rotate in the strong winds (B through D).

4. NON-DAMAGE INDICATORS

The author studied other damaged items that were not included in the original EF-scale document. These included gasoline pumps, rail cars, and oil tanks. Boxcars and hopper type cars are most susceptible to toppling when empty and broadsided by the strongest winds.

4.1 Gasoline Pumps

The author conducted a detailed inspection of toppled gasoline pumps at the Chardele Auto and Truck Plaza located at the intersection of East Ward Line Road and Fruge St. in Lake Charles. The gasoline pumps were anchored to pairs of steel angles that contained holes used to secure anchor bolts into the underlying concrete. Steel washers on the anchor bolts bridged the holes in the steel angles. However, the washers were too small and had little bearing. As a result, edges of the washers bent upward slightly while corresponding edges of the holes in the angles were bent downward slightly. These small deformations resulted in the gasoline pumps becoming detached from their foundations under lateral wind loading. Other gasoline pumps had corroded steel angles that failed around the anchors. Refer to Figure 28.

Figure 28. A toppled gasoline pump. The inset image shows a close-up of the bolted connection at the base of the pump. Note the slight downward deformation in the steel angle (yellow circle) and slight upward deformation in the steel washer (red arrow).

At least four trains at the Citgo Refinery in Sulphur, LA had boxcars topple to the west. The boxcars were oriented north-south and were broadside to the strongest hurricane winds. A total of 7 boxcars overturned while the remaining cars remained upright. According to the FCMP tower in Sulphur, peak wind gusts were 96 kts (110 mph) out of the east. Refer to Figure 29.

Figure 29. Overturned boxcars at the Citgo Refinery in Sulphur, LA. The cars were oriented north-south and toppled to the west with the strongest winds being from the east.

4.3 Oil Tanks

The shells of two smaller oil tanks buckled inward at the Citgo Refinery in Sulphur, LA during the hurricane. Both tanks were near empty at the time and their plunger type roofs were positioned near the bottoms of the tanks. Thus, steel walls of the tanks were not supported laterally by their roofs. Both tanks buckled on their northeast (windward) sides. Refer to Figure 30.

Figure 30. Buckled oil tanks at the Citgo Refinery in Sulphur, LA.

5. SUMMARY

The author conducted a damage survey of the Lake Charles, LA area after Hurricane Laura to document the performance of various structures. Peak winds measured by FCMP ranged from a 96 m/s (110 mph) gust in Sulphur to a 115 m/s (132 mph) gust in Lake Charles. Overall, there was very good agreement between expected failure wind speeds for various structures listed in the EF-scale and wind speeds measured during the hurricane.

Many structures failed or sustained severe damage when three-second wind gusts reached 40-58 m/s (90-130 mph). Where catastrophic failures occurred, inherent weaknesses in connections usually were factors in the failures. Many buildings sustained severe damage when windward windows or doors failed, allowing wind to enter and pressurize the buildings, creating additional upward forces on roofs and increased outward forces on leeward walls. Corrosion of steel anchors due to the salt air environment was common and contributed to failures of certain structural components.

Many buildings survived the strong winds because good construction practices provided continuous load paths from the roofs down to the foundations. Even properly anchored manufactured homes survived this major hurricane, sustaining mostly cladding damage. The author came away from this survey proud of the fact there were many success stories where proper attention had been paid during the installation of anchors, bracing, and connections (the building ABCs) such that most buildings survived and damage could be repaired.

6. ACKNOWLEDGEMENTS

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