In the Eye of Ivan

By Kurt Gustafson, S.E., P.E.

As the Eye of the Hurricane approaches, the Structural Engineer starts to squirm at the thought of a Structure he has design being put to such a test...

Hurricane Ivan. Courtesy NASA/Goddard Space Flight Center Scientific Visualization Studio.

The amount of confidence he has in what he has calculated, and the abilities of the construction team all of a sudden seem far removed from the events of the time. Whether a building is truly engineered or not, it must generally comply with minimum building code standards. Historically, many requirements stipulated in model building codes for residential structures were of a prescriptive nature, largely based on experience with typical construction materials and techniques developed for 'normal' circumstances. Hurricane events were largely considered as abnormal events, and one would speculate as to the performance of a structure constructed to meet these minimal requirements.

In the aftermath of Hurricane Andrew (1991), building code officials, model code groups, design professionals, academics and industry organizations began taking a deeper look at the weaknesses of the building mechanisms largely devastated by the event. The large majority of the damaged structures were of the single-family residential category, mostly constructed based on prescriptive code provisions.

In an engineered structure, wind loads have long been a factor in the design of the basic lateral force resisting system (LFRS). The LFRS would take on added significance as the height of the structure increased. When located in a high wind region such as the Florida peninsula, the wind load factor becomes more critical, even for relatively low structures. Wind forces are often resisted by a series of orthogonally arranged walls, frames or braces that make up the LFRS. These systems provide the strength and stiffness of the structure to resist the effects of the wind as well as to provide for the overall stability of the structure. In other words, this prevents the collapse such as envisioned with a stacked 'house of cards'.

For many decades, the cladding systems of high rise buildings have also been scrutinized for the effects of wind on the building enclosure. Glass and curtain wall systems are regularly developed and tested to resist cladding pressures induced by the required wind load event. In a hurricane event, it was found that significant damage occurred because of flying debris. This affected low rise residential structures as well as high rise. As the exterior enclosure was breached by flying debris, the internal pressure of the building would greatly increase, adding to the external uplift pressure on the roof and lifting the sheathing diaphragm panels off the roof. This roof diaphragm is a stabilizing system that ties the structure together, the loss of which could lead to partial or even total collapse.

In the years following Andrew, there was significant testing and research leading to modification in the building codes regarding the requirements of exterior claddings to resist impact forces. There were also increased requirements for tying the roof panels to the structure, and creating a continuous load path, resisting tie requirements.

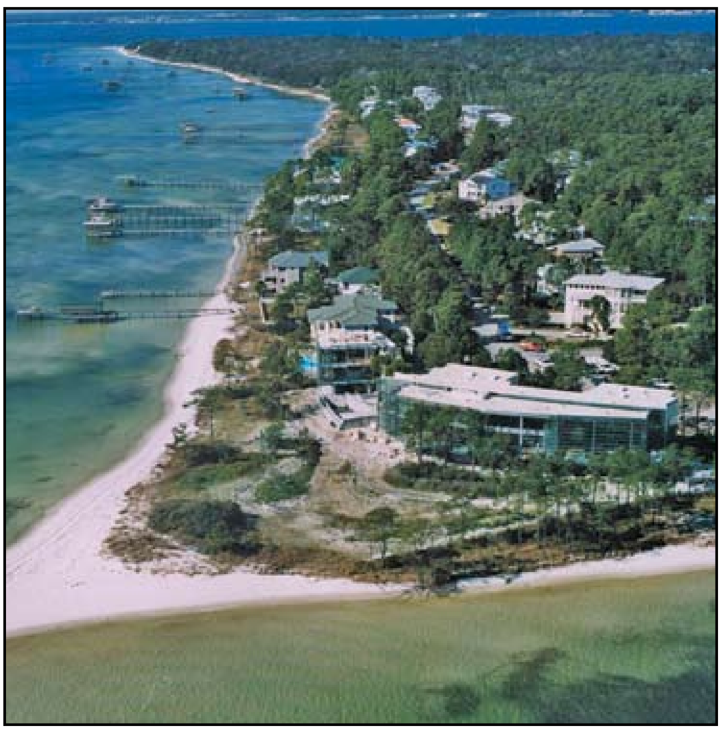
When a structure is constructed on the coast in an active beach zone, it becomes a 'double whammy' on the structural system; initiating both wind and water effects. Structures located in any flood zones must meet certain FEMA requirements. The lowest occupied living level must be elevated such that the bottom of the structure of that level is above the base flood elevation for the site. If the building is in an active beach zone, it must permit the rising water to flow under the low floor and be minimally impeded. The structure must also be founded on deep foundations to minimize the possibility of support erosion due to scouring of the beach zone.

Section of Bridge Destroyed by 'Ivan'.

The building enclosures and structural support elements that are constructed between the ground and raised floor level must be minimized so as not to restrict the flow of the rushing water. When building perimeter enclosures are constructed at this ground level, these must be designed and constructed to resist lateral pressures under 'normal occurrences', but be able to breakaway in the abnormal hurricane event. The vertical support structural elements which pass through the grade level zone must also be minimized so as to not impede water flow, but must be designed to resist the rushing water forces as well as impact of floating debris.

When a major hurricane hits head on, and a structure withstands the fury of the storm with only superficial damage, the engineer breathes a sigh of relief. He or she then starts looking for reasons as to what set this structure apart from surrounding structures that did not fare as well. This will increase understanding and may give ideas that can be incorporated in the next design. This same level of inquisitiveness is used on a larger scale by engineers, material standards groups, code authorities and others when evaluating the destruction caused by such a major event. Such information is extremely beneficial in developing methods of enhancing the structural resistance to better withstand the extreme forces of such future events.

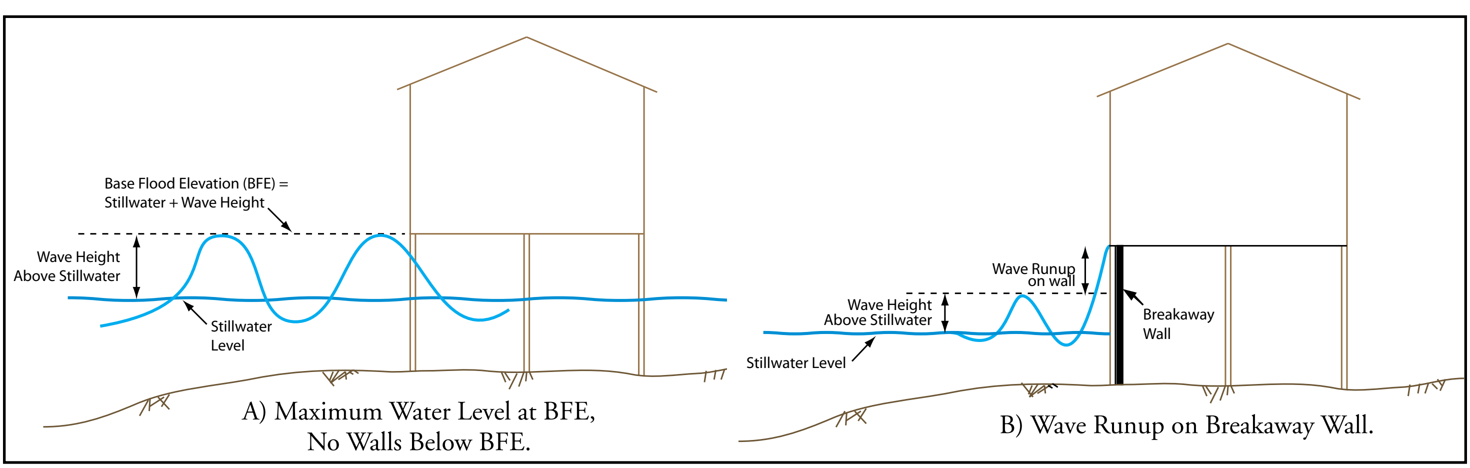
Barrier Island in Florida Panhandle / Sea Breeze



Mullet Residence at tip of Barrier Island.

The Mullet Residence, situated on the Florida Gulf Coast, was just nearing completion when Hurricane Ivan was bearing down toward the prominent point of the barrier island where it stood. This had been a rather unique project for the design team, since they had exceptional support from the Owner. This gave the team opportunity to investigate alternatives of construction types not typical to residential structures along the Florida coast.

The design of such a coastal structure required a sensitivity of its proximity to the Gulf of Mexico and subsequent location within hurricane alley. Local building codes required the lateral loads to be based on a maximum sustained wind speed of 110 mph. Based on the need to protect the structural system of the house against a relatively moderate strength hurricane, the design team decided to increase the base wind speed to 150 mph. The increased wind speed yielded an average lateral applied load of 58 psf. Reinforced concrete shear walls at the elevator shaft and MEP cores were used as the primary lateral load resisting system. In the fall of 2004, the project was nearing completion as Hurricane Ivan formed in the southern portion of the Gulf of Mexico. As it progressed to the north, Ivan strengthened to a category 5 hurricane (maximum sustained winds of 150 mph or more). At approximately



Effect of Enclosure Wall on Waves. Courtesy of FEMA Coastal Construction Manual.

Structural Steel 1st Floor Diaphragm Supported on Sprouts.

2:00 am on September 16th, 2004, Ivan made land-fall directly over the house. At that time, Ivan's strength had dissipated to a category 3 hurricane, with maximum sustained wind speeds of 130 mph. Under the forces exerted by Hurricane Ivan, the project did not suffer any structural damage. The 'breakaway' walls that had been provided in the interstitial space between the grade and raised living level had given way as expected, minimizing the effect of the rushing water flow on the structure.

Steel Sprouts Supporting Mullet Residence.

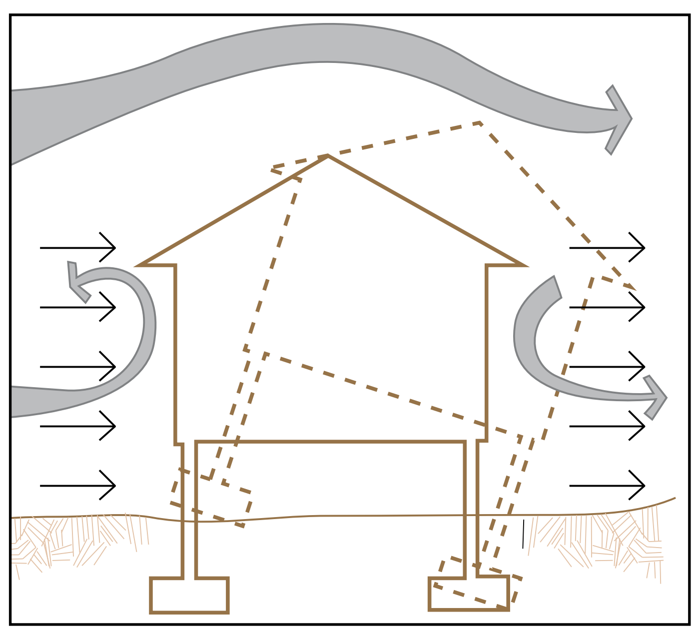
Many surrounding structures, including the major bridges leading to the barrier island, had not fared as well. The Interstate 10 Bridge across Escambia Bay was shut down as it incurred heavy damage; a stretch of ¼ mile of the bridge was entirely destroyed. Numerous boats were sunk or stacked at the Bayou Grand Marina at NAS Pensacola. In the immediate area surrounding the Mullet Residence, all of the timber houses sustained various structural failures.

Looking back at why the structure had fared so well, as compared to surrounding structures, is of course always a matter of conjecture and opinion. One of the very unique characteristics of this structure was the support system in the interstitial space between grade and the floor level raised above the base flood elevation. The author believes that this unique support system played a large part in helping the structure come through the storm so well.

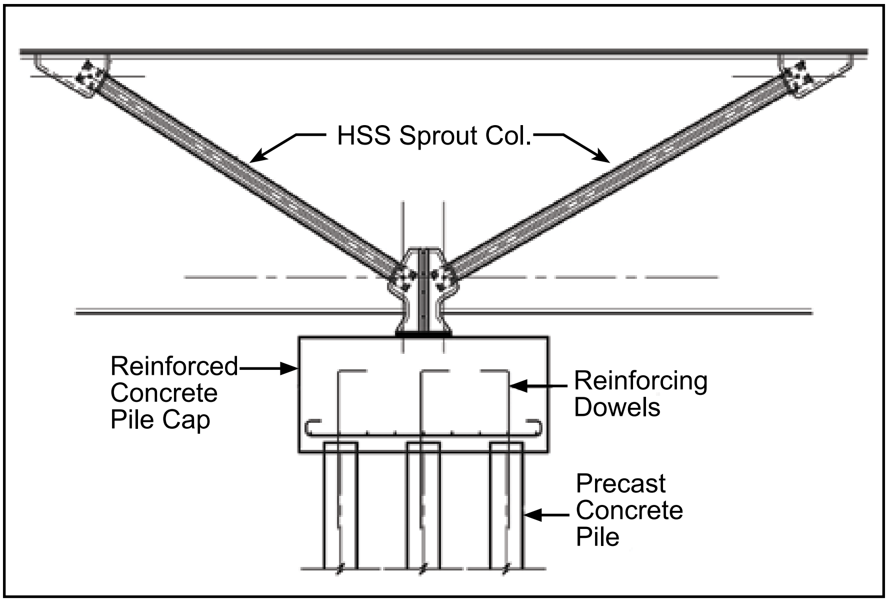
Many structures constructed in active beach zones, commonly called 'stilt structures', have a series of closely spaced gravity supports for the raised structure. Sets of diagonal bracings between the vertical 'stilts', installed in orthogonal directions, provide for stability to resist lateral wind and water forces. The floor construction is often of wood framing of relatively short span, leading to the close spacing of the supports.

Single-family residential structures are typically of only one or two raised living levels. Thus the gravity column loads are relatively small compared to structures with longer span floor systems and larger column spacing. The necessity of deep foundations often leads to selection of some type of a pile system. The gravity load capacity of a single pile is often adequate to accommodate the relatively light loads of the closely spaced columns. If a single pile is used for each column, the solution is often to drive the pile and have it cantilever above grade to support the raised superstructure. Driving tolerances of pile locations must be accounted for in the method of attachment to the superstructure. Another less used method for single piles is to cut the pile off below grade, provide a pile cap, and support a column on top of the pile cap. Of course, this is like placing one pole on top of another, and trying to hold them together at the splice. To accomplish this, grade beams must brace the pile caps in orthogonal directions to laterally stabilize the system.

When the pile cap method of support is used, it is preferable to have at least three piles per cap to stabilize the system in multiple-directions without the need of grade beam braces for the caps. The supported column can then be located near the centroid of the pile group, minimizing eccentricity, and accommodating necessary tolerances of the pile driving operation.



Wind Overturning Forces on Structure. Courtesy of FEMA Coastal Construction Manual.



Typical Sprout Support.

produced a building that visually appeared to float above the ground. The sprouts are constructed of 8-inch diameter stainless steel tubes and support W18 girders at the first floor level. A total of 11 sprouts consisting of (42) 8-inch diameter columns were used to support the main house superstructure. The sprouts are supported by hubs composed of 1 ½- to 2-inch thick stainless steel plates.

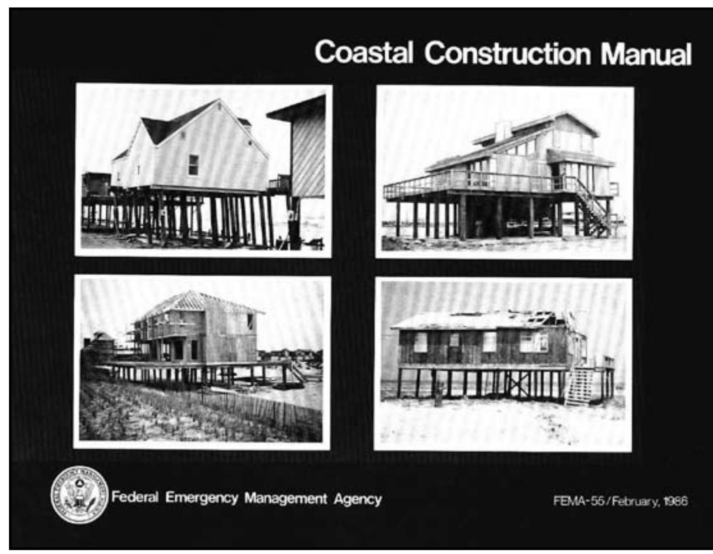
This sloped column concept worked well in conjunction with the structural desire to group columns at the foundation in order to facilitate the foundation design. The engineering team first investigated using vertical columns to support the floor framing raised above the base flood elevation. They found that column loads would require only one or two piles for gravity support. This would in turn require a grade beam system between the pile caps for lateral stability. There would also be the need for substantial bracing between the columns in the interstitial space for lateral resistance and stability.

Using more piles within a group is most efficient if the column loads are consistent with the capacity that the piles can provide. Thus longer spans and increased column spacing can often be accommodated because of the desired minimum 3 piles within the group approach.

The Mullet Residence was rather unique for a residential structure. It consisted of structural steel framing supporting a metal deck with concrete fill. Thus the gravity loads were somewhat greater than the normal wood framed residential structure. The desired construction tolerances for the steel framing were not conducive to the typical cantilevered type of pile support system. Rather, the pile cap and column system was deemed more appropriate for this structure.

Residential coastal construction requires that the main living levels be elevated above the local base flood elevation. In this case, the first floor was 10 feet above grade.

Usual coastal construction utilizes driven wooden piles cantilevering above the ground elevation to support the main living levels. Conceptually, the Mullet Residence differs in that the architect desired to slope the columns and to connect four columns to a single foundation connection point. The creation of the "sprout" element



Cover of FEMA Coastal Construction Manual.

Whereas, the alternate 'sprout' scheme of sloped columns would act as both the columns and bracing in providing for both gravity and lateral stability.

In order to bring the concept of the house floating from the exterior to the interior, several locations of the second floor framing was held back from the main building columns. At these locations, 3-inch diameter hanger rods were used to support the second floor framing. The hanger rods were supported by the composite steel framing at the roof level.

The use of architecturally exposed steel dictated a number of structural design criteria. This included the type of joints that were used (typically mitered), and the type of shear and moment connection details. Architecturally exposed steel requires greater tolerances during fabrication and erection than that of conventional steel framing. Additionally, member proportions, both vertical and horizontal, were required by the architect to achieve the visual appearance that was desired. As an example, the superstructure columns are comprised of (2) 5-inch diameter HSS columns tied together with sculpted plates. This matched the exterior wall horizontal mullion spacing.

Non-Structural Damage caused by 'Ivan' to 1st Floor Soffit.

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Non-Structural Cladding Damage on Core Walls.

Break-Away Wall Collapse (as anticipated).

The primary lateral force resisting system consisted of two reinforced concrete cores, which extended from the large pile caps under each core, to the roof of the two story structure. These cores were designed to transfer the total lateral design wind loads on the superstructure to the foundations. The cores were spaced apart such that minimal torsional effects as required by Code were accommodated. However, in retrospect, the beneficial effect of the 'sprout' system, spaced throughout the footprint of the structure, obviously would enhance the torsional performance of the system. The 'sprout' system, that was initially conceived to primarily address gravity loads, likely became an alternate, if not primary load path, of a 'belts and suspenders' redundancy approach. The engineering team was grateful that the 'sprouts' were in-place and effective when Ivan roared through, as the owner and contractor rode out the hurricane in the structure.▪

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