nexus

Submission Category: Structural Systems

Patrick Allen and Brad Frederick

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Summary Narrative

The proposed Elementary School and swimming pool project for the Reading School District is a project that poses several unique challenges. The Reading School District, located in southeastern Pennsylvania, is among the poorest school districts in the nation. Additionally, crime is a problem in the Reading area, and security in the school is a concern for the School District. The project site is located in a downtown region of Reading at the (fictional) intersection of Thirteenth Street and Park Street. Currently, there are several existing structures on the site that will be demolished to make way for the new school building. An existing elementary school building also exists on the site, and may be kept as part of the project if the School District chooses to do so. Finally, an important provision for the school is the use of the gymnasium as an emergency shelter for the community.

In order to provide the Reading School District with an elementary school that satisfies their requirements and creates a successful learning environment, Nexus developed several goals that drove the decisions for the project. The project team's goals included low life-cycle cost, a versatile building layout, and an integrated design approach. These goals were created in an effort to solve the environmental challenges facing this project while also considering the unique economic conditions of the area.

The Nexus structural team worked with the other engineers and team members to provide a building that is innovative but efficient. Some of these design decisions included the use of Insulated Concrete Form exterior walls, a reduction in the number of columns used in the building, and the use of concentric steel braces and shear walls for the lateral system. Each of these design decisions posed additional challenges that needed to be addressed by the structural team as well as other team members. These challenges will be discussed throughout this document.

Another important aspect of the project is the interdisciplinary collaboration amongst the Nexus team members. Nexus utilized Building Information Modeling (BIM) software to achieve team goals and to ensure quality of the final product. In the end, Nexus feels the team was able to come up with a unique solution that solves the unique challenges of the Reading Elementary School. Moreover, the Nexus structural team believes that the designed structural system provides a cost-efficient and owner-oriented solution that will satisfy the goals of both Nexus and the Reading School District.

Owner Goals

In order to provide a building that best suits the needs of the Reading School District's new Elementary School, Nexus chose to develop goals that would satisfy the owner's needs. Nexus evaluated the specific challenges of this project to develop these goals. For example, the economic conditions of the Reading Area were a focal point for determining owner goals related to short-term and long-term costs.

The first goal established for the building is safety and security. Because of the high crime rate of the Reading area and the poor economic conditions, safety is paramount in an urban elementary school. Nexus sought to design the building in a manner that satisfied the requirements for safety of the young children coming to school each day. Many of the decisions related to safety and security are reflected in the adjustments made to the building's floor plan, that will be discussed later. Additionally, the use of the building as an emergency shelter was an important reason for safety and security to be considered.

Another goal designed to help the building owner is lifecycle and maintenance costs. Again, since the Reading School District faces financial challenges, the up-front cost of the building will be a hugely important consideration for the owner. However, since the building is an elementary school that could potentially be used for up to a century or more, the lifecycle and maintenance costs of the building will be just as important for the owner and the local taxpayers.

Finally, Nexus aimed for the building to be as cost-effective as possible due to many of the same reasons listed above. The up-front cost of the building needs to be balanced with long-term lifecycle costs to best serve the needs of the School District.

Nexus Team Goals

Achieving the listed owner goals is a vital part of delivering a quality project, but Nexus also developed team objectives in order to help satisfy the owner requirements in an efficient manner. Nexus determined there are three main focal points for the project team to work toward while designing the building and its systems.

The most important goal for Nexus as a team is integration. Collaboration between the different disciplines is critical for the success of any project, and Nexus wanted to be sure that the team realized this throughout the course of the design process. Many, if not all, of the decisions made by the Nexus structural team were part of a collaborative process that determined how structural design decisions would affect the other disciplines.

Another objective set by the team is the philosophy of "Reduce, Recover, Reuse." This mindset helped the team to be cost-effective and satisfy the owner goals relating to up-front cost and lifecycle costs. It also helped to establish more communication between the disciplines by ensuring that “Reduce, Recover, Reuse” was feasible for all of the systems in certain situations. This idea was also particularly important when considering that the school will likely be used for a long time.

Lastly, Nexus wanted to focus on using the elementary school as a learning tool for elementary school children to better understand buildings and how they work. This goal helped Nexus to create a more involved learning environment, but it also allowed for different cost-saving techniques such as exposed ceilings that showed mechanical systems, structural beams, piping, and other components. The Nexus goals made it easier for each discipline to make design decisions that would best serve the requirements of the Reading Elementary School.

Structural Team Goals

In order to achieve team and owner objectives, each discipline focused on certain aspects of making design decisions. The Nexus structural team was predominantly concerned with providing a cost-efficient solution that minimizes the number of structural members and also limits the structural system to a reasonable depth. The team also wanted to positively impact the lifecycle cost of the structure by working with the other disciplines. These goals will be evident in the systems design decisions explained later.

The project provided several requirements for the structural team that needed to be addressed. One obvious challenge is the use of the gymnasium as an emergency shelter. In order to design the gymnasium for this condition, a number of factors were considered for other portions of the building as well. Another important requirement of the project is versatility of the floor plan. Since the building is an elementary school that will be used for a long time, Nexus understands that teaching methods will evolve over time and may necessitate changes to the building that should be easily accommodated by the structure. One of the most important project requirements for the structural team is a result of the site conditions. According to the geotechnical report, the site is located on fill that has little soil bearing capacity and is extremely prone to sinkholes. The geotechnical report listed three different options for the foundation system that were each considered and evaluated by the structural team.

Description of Structural Systems

The Nexus structural team took all of the project goals into consideration while selecting and designing the structural systems for the elementary school. The following section of the document will explain each structural system while the rationale behind design decisions will be discussed in a later section.

One important feature of the structural system is the introduction of two expansion joints in the building. The expansion joints are designed to serve a couple of important purposes. First, as will be discussed with the lateral force-resisting system, seismic forces controlled the design of the lateral systems. Due to the geometry of the floor plan, especially near the east wing of the building, a torsional irregularity was a large concern. Therefore, an expansion joint exists where the east wing meets the central wing in order to reduce the effects of torsion on the building during a seismic event. Likewise, where the west wing of the building meets the central wing, another expansion joint was added. This joint also helps to lessen the torsional effects, but it also allows for the design team to consider the emergency shelter a separate structure from the rest of the elementary school.

Foundation System

As mentioned previously, the soil conditions on the site are not favorable. The geotechnical report provided for the site suggested three different systems for the foundation: compaction grouting, site excavation and replacement, and driven piles. After evaluation of the three options and conversations with the construction team, it was determined that the best solution would be driven piles and pile caps. Using the 10” diameter steel piles suggested, the structural team determined that for many of the isolated columns, two piles would be sufficient instead of the three recommended by the report.

The foundation system also features grade beams spanning between pile caps. The grade beams help to support the exterior bearing walls that will be discussed later in this section. A typical portion of grade beam sees a factored load of 17.8 klf over a span of 14 ft. Pile groups are placed at increments of 14ft (half the typical bay span) along the wall in order to limit the span of each grade beam to control depth. The typical grade beam is 24” deep by 16” wide with (6) #9 longitudinal reinforcing bars.

Columns

After reviewing the provided floor plans, the structural team noticed that there were three structural bays in the central and west wings of the building as shown in Figure 1. The bays were sized at 30 ft, 12 ft, and 40 ft. As a cost-saving move, the structural team combined the 30 ft and 12 ft bays into a single 42 ft bay since a 40 ft bay was already being required. Figure 2 shows the new bay configuration. This move eliminates a column line from the building and saves a considerable number of piles for the project. Aside from the interior column line, only four additional isolated columns are required in the building as part of the lateral system.

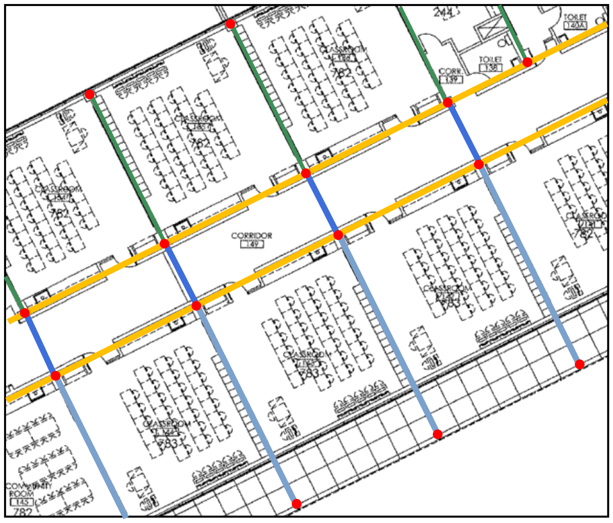

Figure 1: Existing Structural Grid

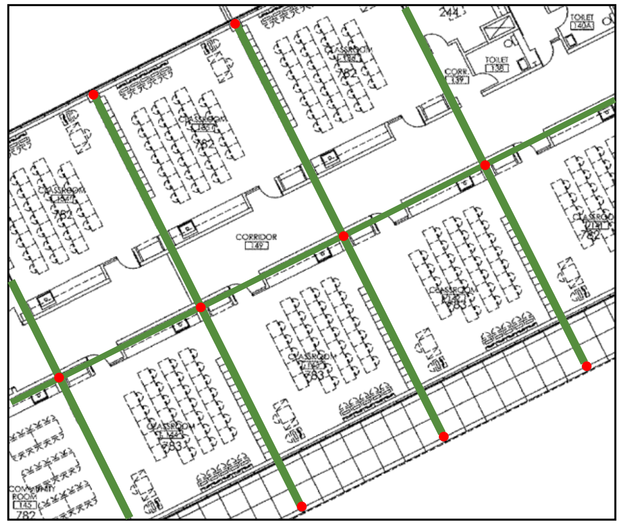

Figure 2: Modified Structural Grid

Exterior Bearing Wall

One of the most unique features of the structural system is the exterior bearing wall system. The system uses 6" thick reinforced concrete bearing walls and Insulated Concrete Forms (ICFs). ICFs are stay-in-place forms built with two pieces of foam insulation held together by plastic bridging. ICFs have a number of advantages including ease of construction due to their modular nature. The ICF system provides a structural purpose for the building, but it also has several thermal advantages and is virtually airtight. The ICF manufacturer also provides forms for beam seats that make it easy to transfer loads from the floor systems. Finally, the ICF walls are also able to be utilized as shear walls for the building's lateral force-resisting system.

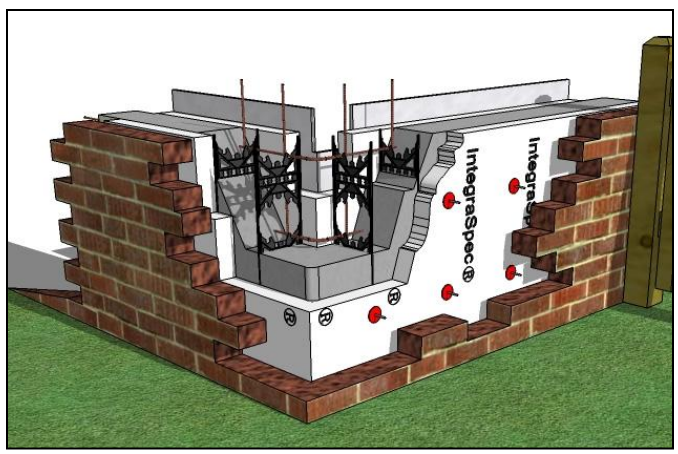

Figure 3: Insulated Concrete Form Wall Cutaway

Floor system

The floor system consists of composite steel beams and girders along with a 3" thick slab on a 3" composite metal deck. The floor system was chosen largely on the desire to use as few columns as possible. Composite deck and W18x46 beams were able to provide the long spans that were required to achieve this, while still providing a manageable structural depth. The 3" slab on 3" deck helps to avoid deflection issues over the long span and also limits the effects of vibrations on the floor system.

Roof System

The roof system over the pool and gymnasium are long span steel joists with roof deck over the pool and 3” non-composite deck and 3” slab over the gym to help satisfy FEMA shelter requirements. The roof system over the classrooms consists of non-composite beams with roof deck. The biggest concerns for the roof were snow drift loads, which were calculated as 38 psf for a school in Reading.

Gymnasium/Shelter

Because the community determined there may be a need for an emergency shelter, the feasibility of allowing the gymnasium to also function as a shelter was investigated, and it was determined that it could be accomplished with little added cost to the project. The gym structure was designed according to the FEMA document P-361, Design and Construction Guidance for Community Safe Rooms. Since the exterior walls are 6” concrete bearing walls, they meet the FEMA projectile requirements. The end walls were able to be designed as concrete shear walls to resist wind forces of a major hurricane. In order to meet FEMA requirements of wind uplift resistance and vertical projectiles, the structural team decided to use a 3”concrete slab on a 3” non-composite steel deck. The roof joists were then upsized accordingly in order to support the added weight. The major additions to the structural system in order to qualify the gym as a shelter included adding the slab to the roof and increasing the size of the roof joists.

Lateral Force Resisting System

Using the guidelines of ASCE 07-05 (a requirement of the Pennsylvania UCC), it was determined that seismic forces are the controlling factor for the design of the building’s lateral force resisting system. The large amount of weight added to the structure by the exterior concrete bearing walls was a significant reason causing the seismic forces to dominate wind forces. However, the exterior bearing walls provide an advantage since they are also utilized as lateral force-resisting shear walls for the building. Since the building is broken into three independent structures, each section is designed slightly different from the others.

The west wing of the building, which features the pool and gymnasium/emergency shelter, is designed with an importance factor of 1.5 since this portion of the structure is considered essential during an emergency situation. Lateral forces in the east-west direction are resisted by the 6”-thick exterior shear walls of the building. Shear walls also provide lateral resistance in the north-south direction of the building, but concentrically braced steel frames are also included to provide lateral resistance for the three-story portion of the structure that includes the library and several third-floor classrooms. The concentric braces are comprised of HSS 6”x6”x1/4” steel members that fit within the thickness of the walls between rooms.

The central wing of the building, which features most of the classrooms and learning spaces, is designed with an importance factor of 1.25 since its structure is independent from the shelter structure. Like the west wing, the central wing uses exterior shear walls to provide lateral resistance in the east-west direction. Since the south façade of the building features an extruded second floor, a continuous bearing wall was not a viable option. Instead, the south façade is built as a curtain wall hung from a steel frame. This necessitated additional lateral force resistance in the east-west direction, so two 8”-thick shear walls were added along the hallway to provide the required resistance. In the north-south direction, the same concentric bracing scheme used for the west wing is used again.

Rationale for System Selections and Solutions

Each decision that was made in designing the structural system was made with the team and project goals in mind. In addition to these goals, the need to have an integrated project guided many of the decisions, especially decisions made in key areas such as the building façade. This section of the report will evaluate the previously discussed components of the structural system and give the rationale in the decision making process. This section will also discuss the considered alternatives, and why they were not chosen in the final design.

Foundation System

The poor soil conditions were the driving force in choosing the foundation system. As previously mentioned, the geotechnical report suggests three options: compaction grouting, excavation and compaction, and driven piles with pile caps. The option to excavate and compact was discussed with the construction team early during the design process. It quickly became clear that this option would be incredibly expensive and probably quite time-consuming. Although it would likely give the structural team the opportunity to design a more simple shallow foundation system, it was determined to be a poor choice because of cost concerns. The second option, compaction grouting, was also looked at carefully. A major concern with using compaction grouting was the unknown subsurface soil conditions and uncertainty about the exact depth of the bedrock. Since the amount of compaction grouting required to successfully reinforce the soil is a large unknown, the cost of the project was again a major concern for the design team.

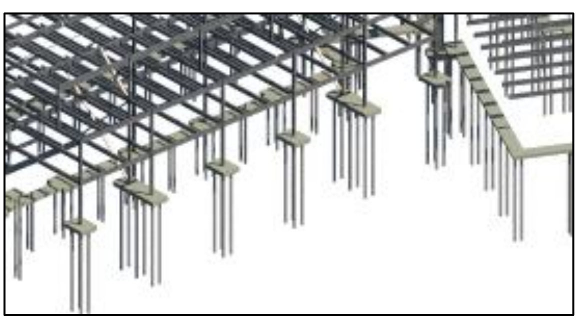

Figure 4: Driven Pile Foundation System

As a result, driven piles and pile caps seem to be the best option for the building due the unknown costs stemming from the uncertainty of the subsurface soil conditions. Although the installation of the piles can be an expensive process, the structural team believed that they could limit the number of required piles to a minimum by making changes to the structural bay sizes in the building. Also, the team investigated the piles recommended by the geotechnical report and determined that for many of the isolated columns in the building, only two piles will be needed as opposed to the recommendation for three piles in the report.

Columns

One of the important goals for the structural team to save money was to minimize the cost of the foundation system by limiting the number of driven piles required for the project. In order to do this, the team wanted to use as few columns as possible in the building. The team noticed that in the three-bay configuration proposed by the original building floor plans, the bay sizes were 30 ft, 12 ft, and 40 ft. Since a 40 ft span was already part of the structural layout, the team decided that combining the 30 ft and 12 ft spans into a single 42 ft span would be an economical decision. This way, the building only has a single line of isolated columns in most portions of the structure, essentially cutting in half the number of required pile caps and piles for isolated columns. Even with the increased span, the loads on the interior columns were not increased significantly enough to require more than the recommended three piles per pile cap.
To use the central wing corridor as an example, the column size required is a W12x87 which carries a strength capacity of 925 kips at an un-braced length of fourteen feet. In conclusion, the decision to eliminate a column line from the structure seemed like a logical one based on the dimensions of the floor plan, and it is also a great way to improve the cost-efficiency of the structure.

Exterior Bearing Wall

The exterior bearing wall system for the building serves a number of purposes. The walls are used as part of both the gravity system and lateral system of the structure. However, another important reason the design team opted to use Insulating Concrete Form (ICF) walls is to provide thermal insulation. The ICF wall solution is one that was reached through discussion and research among both the structural and mechanical designers. The ICF walls help to provide significant savings in lifecycle costs of the building by reducing the loads on the mechanical system. The construction team also saw many advantages in using the ICF wall system. Not only are the ICF blocks easy to install due to their modular nature, but the system greatly reduces the cost of formwork and the labor that is involved in building and removing formwork.

In addition to providing benefits to the mechanical systems, the 6” thick ICF walls designed for the building proved to be a great choice for the structural system. The walls are useful for both the gravity and lateral systems, which will be discussed next in this document. Additionally, the ICF walls help contribute to the safety and security of the building. As will be explained with the emergency shelter, the walls also provide adequate protection against projectiles. Moreover, the strong exterior wall system can provide against gunfire. This is a hugely important characteristic of the wall due to the high crime rate in Reading.

Floor System

One of the challenges resulting from the increased structural bay sizes is the long spans that must be crossed by the floor beams. The team determined that it was best to span the beams in the long direction of the bay and the girders in the short direction. Even though this configuration requires slightly deeper beams, it greatly reduces the required girder depth. Based on the direction in which the mechanical duct runs through the building, it was necessary to limit the depth of the structural system running across the hallway. This was an important factor in choosing a structural floor system.

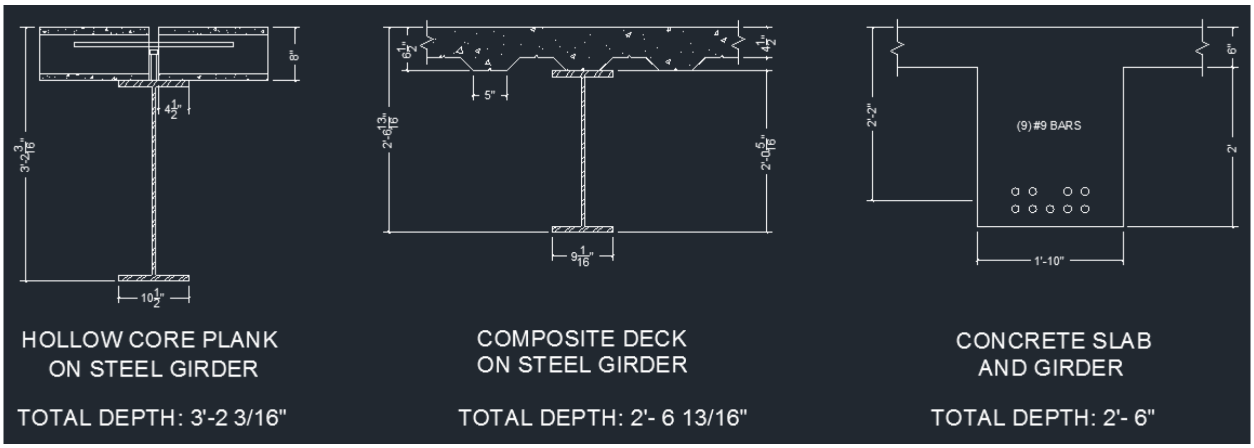

Figure 5: Comparison of Floor System Options

The structural team came to the conclusion that a steel frame with composite floor deck is the most appropriate choice for the building. The team investigated three options for the floor systems: steel framing with hollow-core concrete planks, a concrete frame with a one-way slab and beams, and steel framing with composite deck. A comparison of the required depths for each system shows that the steel frame with composite deck provides an acceptable structural depth. In a typical 40 ft by 28 ft bay in the central wing of the building, the structure uses W18x46 floor beams spaced at 9'-4". The girders crossing the 28 ft span are W24x68 section beams. The use of a steel structural system was also a preferred choice of the construction team since steel is the more common framing system in Reading. Subcontractors in the area are likely to have more experience with steel frame buildings, so using steel for this project seemed like a logical decision.

Originally, the team designed the floor system with a 4-1/2" slab on 3" deck in order to achieve a two-hour fire rating. After investigating the International Building Code more thoroughly, it was determined that the structural system does not need to be fire-rated so long as the entire building has a sprinkler system (the code evaluation is outlined in the Appendix). The team opted to include a sprinkler system in the building, and as a result, the slab thickness was reduced to a 3" slab on 3" metal deck. This size slab was chosen in order to prevent excessive deflection and to help prevent floor vibration issues. Vibration in the floor system due to the long span of the beams was a concern that the structural team wanted to investigate more thoroughly. To do this, the team reviewed a document on office floor vibrations (*Preliminary Assessment for Walking-Induced Vibrations in Office Environments,* Hanagan and Kim). After reviewing this document, it was determined that the designed floor system configuration will not be sensitive to vibration issues. In fact, the large span of the floor actually provides better performance against vibrations than a span of roughly 30 ft that would have existed prior to the change made to the structural bay sizes.

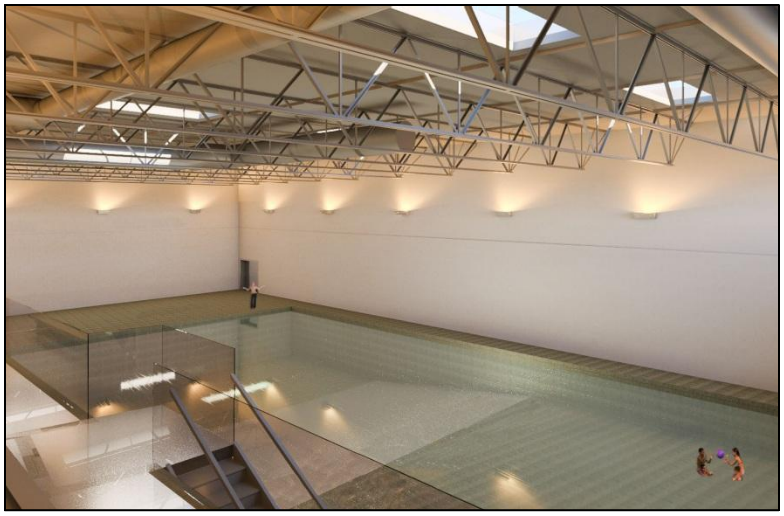

Figure 6: Pool Roof System

Roof System

Long span steel joists were chosen to be used in the pool and gym areas not only because of the long spans, but also since the exterior concrete bearing walls are available to support the roof system. Since there is no need for interior columns in these spaces, the depth of the joists was controlled by optimizing the joist spacing in both rooms.

The roof over the classrooms is supported by steel beams and roof deck. This was preferred over using roof joists in order to keep a reasonable structural depth. Due to the long spans that would be required by the joists, deep joist sections would be required to control deflections. The biggest concerns pertaining to roof loads throughout the building were the snow loads and snow drift loads. A local provision of 35 pounds per square foot of ground snow load was used in calculating the snow loads. Because of the different roof levels, snow drift is a concern, and it was found that the average snow drift load is 38 pounds per square foot. This was used when designing the roof system for all of the two story-height roofs.

Gymnasium/Shelter

FEMA document P-361: Design and Construction Guidance for Community Safe Rooms, was used in order to design the gym as a community shelter. The need for a community shelter was determined by the school board along with the community. The project documentation suggested the need for a “community shelter in the event of a power outage or emergency.” As discussed earlier, it was determined that the gym could be designed as a FEMA certified community hurricane shelter without much added cost. The roof material was changed from roof deck to a 3” slab on 3” deck in order to add mass to the system and prevent uplift. The steel long-span joists were slightly enlarged from an initial design of 36” to 40” in size in order to support the increased weight of the roof. No windows or skylights were put into the gymnasium. While this isn’t ideal for a normal gymnasium, it is ideal for a hurricane shelter and to prevent projectile penetration through windows. This eliminated the need for expensive impact-resistant glass. It was determined by the project team that it made more sense to not have to use projectile resistant windows and to not have significant day lighting in the gym, which is typically artificially lit anyways. The resilient concrete exterior walls are helpful for creating a shelter as well due to their ability to resist projectiles.

Lateral Force Resisting System

During the design process, it was discovered that an important consequence of using the exterior concrete bearing walls in the building is the large increase in weight of the structure. Due to the high weight of the building because of the bearing walls, it was discovered that the seismic loads on the building control the lateral design over the wind loads. Another challenge that arose from this situation was the effect of torsion created by the unique geometry of the building floor plan. Especially where the central wing and east wing of the building form sharp corner, torsional effects became a concern for the structural team. An investigation of some earthquake design techniques suggested that an attractive option for reducing the torsional forces was to isolate separate wings of the structure by adding an expansion joint. This became another major decision made by the structural team for the design. Although several columns were added to the structure at the expansion joints, adjacent columns are still able to share a pile cap. This was especially important to the team since minimizing the number of piles and pile caps was a driving factor for many of the other decisions made for the structural system.

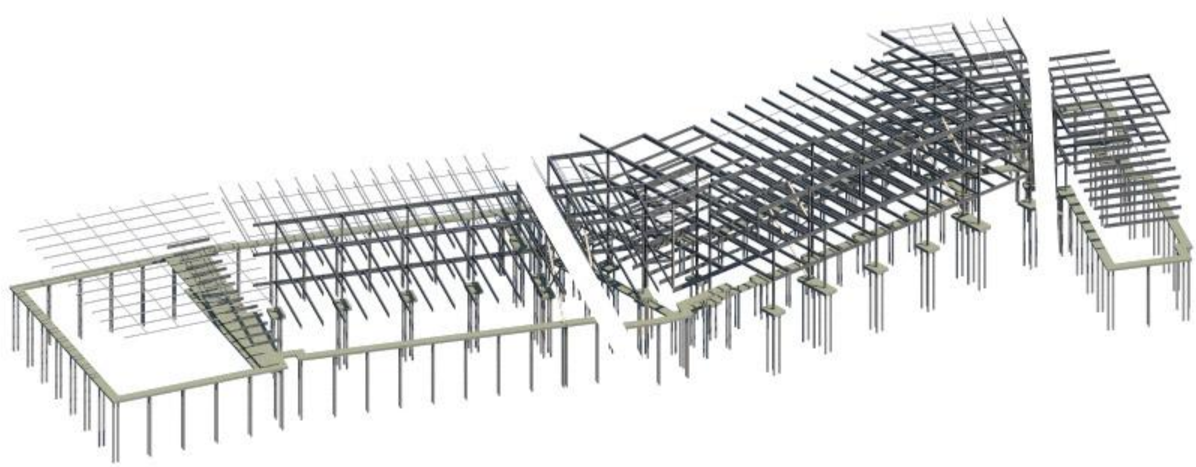

Figure 7: Illustration Showing the Divided Structure Segments

In addition to separating the structure between the central and east wings, the structural team also saw advantages to separating the structure between the central and west wings as well. Since the west wing includes the emergency shelter, the building requires an importance factor of 1.5 for seismic loads according to ASCE 07-05. However, isolating the west wing of the building from the rest of the structure would require that only the west wing has an importance factor of 1.5. The rest of the building can be considered as just an elementary school, and therefore use an importance factor of 1.25. This change was useful in helping to reduce the magnitude of the seismic forces acting on the building.

In each of the three wings of the building, the east-west direction lateral system utilizes the exterior bearing walls as shear walls. For simplification, since the walls are interrupted by classroom windows, the shear walls in those areas are assumed to be 7 ft long segments. The west wing of the building uses shear walls in the north-south direction as well. However, in order to provide lateral support for the third floor of the west wing in the north-south direction, two lines of concentric braces were added. The same type of braces are used to provide lateral resistance in the north-south direction for the central wing since this wing is unable to rely on shear walls in the north-south direction. The designed braces include HSS 6x6x1/4 tubes that fit into the walls between classrooms. Like the west wing, the central wing uses two lines of bracing to provide the required resistance. Because the south side of the central wing uses a curtain wall system instead of a bearing wall, two 8" thick shear walls were added along the hallway to meet the demand of the lateral forces. The east wing of the building is able to rely on the exterior bearing walls in both directions to provide adequate resistance.

<u>ETABS Modeling</u>

In order to more accurately evaluate the structure's lateral systems, the team created an ETABS computer model of each of the three wings of the building to analyze forces and check displacements. The ETABS model was important in determining the size of the expansion joints between the separate building wings. The models showed that the maximum displacement for a structure at any of the expansion joint locations was never greater than 1". Therefore, it was determined that a 2" expansion joint will be satisfactory. In order to more accurately simulate the behavior of the exterior bearing walls, the model walls are meshed into 12" squares, and the wall material properties are defined to have half of the actual modulus of elasticity in order to simulate a cracked wall section. Additionally, 6 ft deep coupling beams are modeled between walls to simulate those walls which include classroom windows. The modal response time periods from these models are used to help determine the C_s coefficients and the seismic forces on the building.

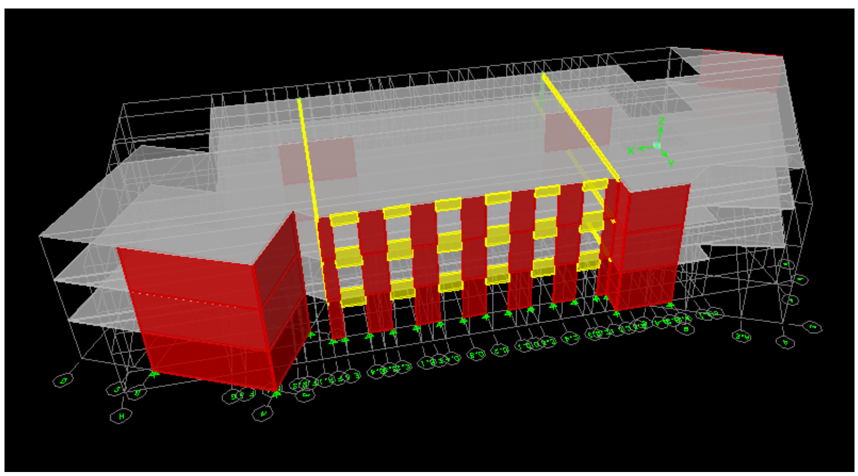

Figure 8: Sample ETABS Model Showing Walls and Coupling Beams

<u>Look-ahead</u>

For the remainder of the project, the team will focus on refining the ETABS models and examining the lateral loads. In addition, the team will also finalize designs for the pile caps and other foundation components. The team will perform spot checks at various locations around the building to ensure that the building meets all requirements for strength and deflections. Finally, the structural team will work with the other disciplines to complete the BIM models and check that all systems and components are modeled accurately. The project team will perform clash-detection tests and determine potential trouble spots in the building. As always, the structural team will continue to review the structural system and determine if there are additional cost-saving opportunities.