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Robert College Seismic Upgrade

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Abstract

The original four buildings at Robert College in Istanbul, Turkey were constructed between 1910 and 1914 along a north-south axis on the western side of the Bosphorus Strait. Sage Hall, the most southerly building is a four story L shaped structure housing girls' dormitories. Gould hall in the north is the central administration, reception and library building and is a U shaped five story structure. The buildings are all of concrete with plain concrete bearing walls on the perimeter and an interior composite framing system and all are supported by footings on limestone or shale. Floors are of reinforced concrete

Although the city of Istanbul is not on a fault, the region has experienced some serious earthquakes in the past 90 years. As both Sage and Gould Halls were not specifically designed to resist earthquakes and have survived relatively intact with only some cracking at the corners of the concrete facade. A study was undertaken to achieve three objectives:

- Evaluate the seismicity of the region and of the site to establish design criteria for analysis of the structures based on the maximum seismic events expected in the future..
- Analyse the structures to evaluate conformance with seismic codes and define areas of the structure which need to be strengthened.
- Design a repair scheme that takes into account both the historical designation of the buildings and the structural requirements. Also consider the need for keeping the facility open during the repair process other than for a short summer recess.

This paper describes the process undertaken to resolve the need for seismic upgrading of these historical structures, alternatives that were developed and the conclusions reached. Finally, the current status of the work will be described.

Keywords: Concrete structure, earthquake design, frame analysis, shear walls, CFRP Fabric

1. Introduction

The original four buildings at Robert College in Istanbul, Turkey were constructed between 1910 and 1914 along a north-south axis on the western side of the Bosphorus Strait. Sage Hall, the most southerly building is a four story L-shaped structure housing girls' dormitories. Gould hall in the north is the central administration, reception and library building and is a U-shaped five story structure. The buildings are both constructed with plain concrete bearing walls on the perimeter and an interior composite framing system all of which are supported by footings on limestone or shale. Floors are of reinforced concrete

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- Evaluate the seismicity of the region and of the site to establish design criteria for analysis of the structures based on the maximum seismic events expected in the future.
- Analyse the structures to evaluate conformance with seismic codes and define areas of the structure which need to be strengthened.
- Design a repair scheme that takes into account both the historical designation of the buildings and the structural requirements. Also consider the need for keeping the facility open during the repair process other than for a short summer recess.

Evaluation of existing conditions, assessment of the earthquake ground motion hazard at the College site, and structural engineering analysis and calculations determined that both Sage and Gould Hall buildings require structural strengthening to withstand a code-level earthquake and provide life safety protection to the occupants.

After the 1999, magnitude 7.4 earthquake in Izmir, the trustees of Robert College concluded that the buildings could not withstand the seismic loads imposed by the 1998 Turkish Building Code requiring loads from a magnitude 7.5 earthquake. This paper describes the process undertaken to resolve the need for seismic upgrading of these historical structures, alternatives that were developed and the conclusions reached. Finally, the current status of the work is described.

1.1 Robert College

The site of the Robert College of Istanbul is located off Kuruçeşme Avenue in Arnavutköy on the western side of the Bosphorus Strait in Istanbul, Turkey. The site was built on a graded terrain which moderately slopes downward towards the Bosphorus on the East. The Robert College complex was constructed between 1910 and 1914 from plans developed by Shepley Rutan & Coolidge Architects of Boston . The buildings are historically significant as they utilized a modernist aesthetic concept – the use of exposed concrete, *béton brut,* which soon became the focus of modern architecture. On the other hand, the homogenous and rather formal expression of the buildings comes from its Beaux Arts design style.

Sage Hall is the southernmost building in a row of buildings on the campus extending in the North-South direction. The building plan is L-shaped with lengths of 35.4 m and 24.4 m (116' and 80') for the outer edges and a width of 15.2 m (50'). The four-story structure has story heights of 4.11 m (13'-6") except for the first story which is 3.50 m (11'-6") tall. The first story is referred to as the basement in the original design drawings although it is above grade and it will be referred to as basement in this paper for consistency.

Gould Hall is the fourth building from the South on the North-South row of main College buildings (Fig 1) and is the center piece of Robert College. The building plan is essentially a C-shape with dimensions of 54.0 m by 25.0 m (177' by 82'). The five-story structure has story heights of 4.11 m (13'-6") except for the first story which is 3.50 m (11'-6") tall. The first story is also referred to as the basement in the original design drawings although it is partially above grade. Gould Hall is the heart of the Robert College buildings, the reception point of all – after a set of stairs on the main pedestrian approach. Its colonnaded front forms a welcoming alcove with projecting arms on both sides. An impressive loggia above the main entrance commands a view of the sloping main field and the Bosphorus beyond. It is the largest building of the five originally constructed buildings and the most elaborate. All exterior walls are exposed concrete, *béton brut*. The dominant character of the building finds its reflection in the form of its free standing columns, stairs leading to the entrance, double-story arched openings, and central location.

1.2 Structure

The structural system of both buildings consists of plain concrete bearing/shear walls along the building's perimeter, and a composite frame system in the building's interior. The perimeter walls have varying thickness along the height and along the perimeter of the building: varying from 610 mm to 710 mm (24" to 28") at the basement and first stories, and 510 mm to 610 mm (20" to 24") at the second and third stories. The interior face of the perimeter walls has an approximately 25 mm (1") thick layer of plaster on a wire lath. The wire lath is supported by metal spacers that are attached to the perimeter concrete walls creating an air gap between the plaster and the concrete wall. The size of the air gap varies depending on its location relative to the perimeter walls.

Figure 1

The interior frame system is composed of steel built-up columns and standard shape floor beams with riveted connections encased in plain concrete. These connections are also known as partially restrained moment connections and they can sustain moments up to 50% of their beam moment capacities according to various tests performed on such connections with no concrete encasement as reported by the Council on Tall Buildings and Urban Habitat (1993). Higher moment capacities can be expected for the concrete encased connections. The columns are I-shaped sections built-up from four L-shapes (angles) and a plate, and are encased in rectangular shaped concrete columns. The floor beams are mostly I-shapes with some double angles across the hallway. The connection details on the original construction drawings show that the floor steel beams frame into the orthogonal perimeter beams at the floor levels. These riveted connections with shear tabs are embedded deep inside the concrete perimeter walls. The steel frame system extends into the attic and forms cross-diagonal braces connected to steel rafters supported on perimeter walls. The roof is cross-hipped and covered with clay tiles.

Both Sage Hall and Gould Hall are in relatively good condition given the age of the buildings. Both structures have sustained minor damage during their lifetimes in the form of perimeter wall cracks at window corners and arched headers, concrete spalls at window lintels, some water damage in the attic, and corrosion of reinforcing bars and steel sections embedded in the lintels and attic slabs.

2. Earthquake Ground Motion

The seismic hazard near and around Istanbul is dominated by two major sources of seismic activity: the northern branch of the west end of the North Anatolia Fault (NAF) zone and the Marmara Sea Basin (MSB) zone.

The greater area of the Marmara Sea Basin has been tectonically active, especially in the last 100 years. Since this region has always been a major trade route and Istanbul the capital of three empires (Roman, Byzantine and Ottoman), there is a very rich historical and instrumented record regarding earthquakes, spanning over 2000 years.

1. The most important sources of seismic activity in the region where the Robert College buildings are located are the north branch of the western extension of the North Anatolian Fault in the Gulf of Izmit and the zone of strike-slip and normal faults at the Cinarcik Basin 20 km south-east of Istanbul.
2. If one adopts the time-independent Poisson model, the seismic hazard in the region around Istanbul has not changed significantly since the 1999 Izmit and Duzce earthquakes. If one adopts a time-dependent renewal model, the hazard around Istanbul has increased moderately.
3. Near field effects are not likely to influence the ground motions at the sites because the nearest source is about 25 km away.
4. The building sites are founded on bedrock so no site response need be considered.
5. The Turkish Seismic Design Code recommended spectra for the sites are quite conservative and adequate to represent the design ground motions, compared with the most recent 10% in 50 years hazard estimates.
6. As a conservative choice, the design spectrum for site class Z2, shown in Figure 2 was adopted as a single measure of the expected ground motions at the sites.

3. Lateral Force Resisting Systems

For Sage Hall, we determined that it would be beneficial to utilize and strengthen the existing lateral structural system of the building as opposed to providing an alternative system such as the addition of new shear walls or braced frames which would also have required strengthening of the floor slabs and foundations in addition to occupying valuable interior space. For Gould Hall, considering the relatively complex plan layout of the building and the discontinuity of the interior columns on the library floor, we also determined that it is beneficial to utilize and strengthen the existing lateral structural system of the building as opposed to providing an alternative system such as the addition of new shear walls or braced frames which would also require strengthening of the floor slabs and foundations in addition to occupying valuable interior space. Retrofitting the existing system is less invasive and less disruptive for the occupants, and will conserve the functionality, architecture and heritage of the College as well.

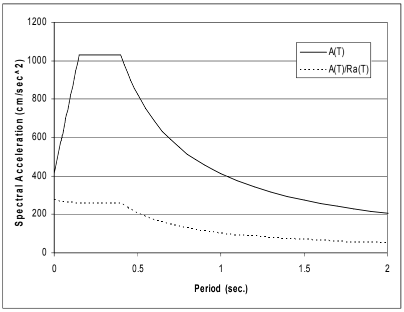

Figure 2

The lateral inertia loads are resisted by the perimeter shear walls in the in-plane direction, which is along the direction of the ground acceleration. The out-of-plane loads on perimeter walls oriented perpendicular to the direction of the ground acceleration are transmitted to the roof diaphragm and floor slabs and finally to the in-plane perimeter shear walls and down to the foundation. The interior composite frame also contributes to lateral load resistance, though not as much as the perimeter in-plane walls.

For Sage Hall, the system behavior is illustrated in Figure 3, which shows the load path for the lateral force resisting structural system solution for ground motion in the North-South direction. The continuity of the load path is attained by the connectivity of the building components to each other in the structural system. The components in this load path that may have a potential weakness in resisting earthquake loads were evaluated. This involved checking for out-of-plane bending of the perimeter walls, the in-plane diaphragm action of the floor slabs that transfer loads to in-plane perimeter walls, the in-plane shear and bending of the perimeter and interior walls, and the shear transfer in the floor slab to perimeter wall connections.

For Gould Hall, the system behavior is illustrated in Figure 4, which shows the load path for the lateral force resisting structural system solution for ground motion in the East-West direction. The continuity of the load path is attained by the connectivity of the building components to each other in the structural system. The components in this load path that may have a potential weakness in resisting earthquake loads were evaluated. This involved checking for out-of-plane bending of the perimeter walls, the in-plane diaphragm action of the floor slabs that transfer loads to in-plane perimeter walls, the in-plane shear and bending of the perimeter and interior walls, the shear transfer in the floor slab to perimeter wall connections, and the biaxial bending in the portico columns.

Structural engineering analysis and calculations were performed for the seismic evaluation of Sage Hall. An ETABS computer model of Sage Hall was prepared to include fixing the hinged connections between the perimeter wall spandrels and piers, adding out-of-plane bending behavior to the perimeter wall piers that were otherwise in-plane membrane elements only, using cracked section properties instead of uncracked properties regarding the in-plane and out-of-plane bending of the concrete perimeter walls, providing a finite element mesh for the unmeshed perimeter wall pier shell elements, and inputting a seismic demand in the form of a response spectrum in the building's two orthogonal directions based on Life Safety requirements of the Turkish Seismic Design Code (TSDC 2007). Figure 2.2 shows the modified ETABS computer model for Sage Hall.

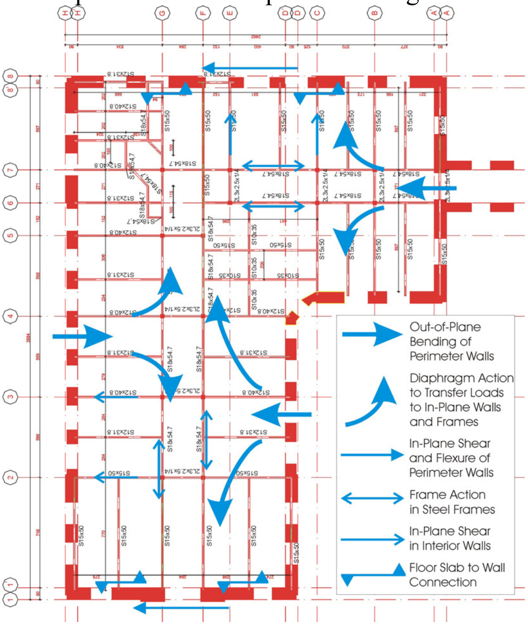

Figure 3

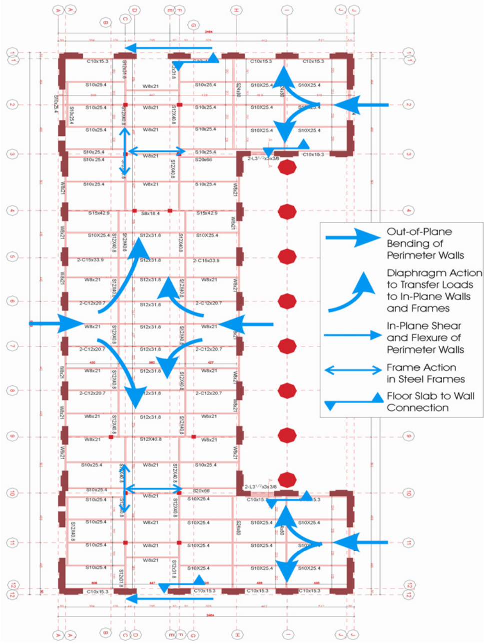

Figure 4

The results of this ETABS computer model analysis were used to determine the factored earthquake demands on various components of the lateral force resisting system and compared to the factored capacities of the building components and tabulated in the form of demand-to-capacity (D/C) ratios. Wherever the D/C ratio is larger than 1.0, it indicates that the earthquake demand on the building component exceeds its capacity, thus requiring structural strengthening.

<u>Perimeter Wall Piers</u>: The piers are those components of the perimeter walls that are located to the right and left of the window openings. The in-plane shear strength of the perimeter wall piers was calculated based on the guidelines for the seismic retrofit of

existing buildings (ICBO 2001) and the concrete building code (ACI 318-05) equations for plain (unreinforced) concrete in shear. The shear strength of the piers includes contributions of the concrete ($1.33\sqrt{f'c}$) and the axial load on the concrete. The compressive strength of concrete (f'c), which is used in the shear strength calculations, is based on the actual in-place strength as derived from the concrete core test results. The calculated in-plane shear capacity for each perimeter wall pier at each story in Sage Hall is compared to the earthquake demand on that pier, and the corresponding D/C ratio determined. We found that the D/C ratios are larger than 1.0 for all piers with the exception of a few of the piers at the top story. Furthermore, the D/C ratios for the piers) located along the building's transverse (North-South) direction are larger than the D/C ratios of the piers along the building's longitudinal (East-West) direction. Therefore, most of the perimeter wall piers need structural strengthening for in-plane shear, especially those piers aligned in the North-South direction. Similarly we determined that all of the perimeter wall piers require structural strengthening for in-plane bending, especially those piers aligned in the North-South direction.

The vertical axial stress demand on the wall piers is small compared to the axial compressive strength of the wall piers. The large axial strength is achieved by the large cross-sectional area provided by the thick perimeter walls. Hence, the perimeter wall piers do not need strengthening for vertical compressive earthquake load demand. Some of the wall piers show a net tensile load demand that is greater than their tensile strength; however, it is expected that the strengthening of the piers for flexure will also provide the necessary capacity in tension.

The out-of-plane bending strength of the perimeter wall piers is calculated based on the ACI 318-05 equations for plain concrete in bending and was found to be such as not to require structural strengthening for out-of-plane bending.

Parapets, Perimeter Wall Spandrels and Perimeter Wall Pier-to-Spandrel Joints were also found not to require strengthening. Furthermore, interior walls and floor slabs were determined to have adequate capacity.

Roof Diaphragm and Framing: The in-plane shear strength of the single straight-sheathed wood diaphragms of the attic floor and the hipped roof was calculated based on FEMA 356 (2000). The diaphragms do not have sufficient capacity to resist the shear demand at the roof level. However, the steel cross-diagonal braces made up of double-angle sections together with the wood diaphragms have enough capacity to transmit the shear forces across the building from one perimeter wall to the opposite wall. Based on our observations on site, the perimeter walls are interconnected at the roof level to form diaphragm action. This connectivity is provided by a line of steel profile located around the periphery of the attic floor and embedded in the perimeter walls, which is connected to the cross-diagonal braces via the attic floor steel framing and the steel roof rafters.

An ETABS computer model of Gould Hall was prepared as for Sage Hall with the same attributes as those used for Sage Hall. The results from this ETABS computer model analysis were used to determine the factored earthquake demands on various components of the lateral force resisting system of Gould Hall.

Similarly to Sage Hall, it was determined that most of the perimeter wall piers need structural strengthening for in-plane shear, especially those piers aligned in the East-West direction and strengthening for in-plane bending, especially those piers aligned in the East-West direction.

All other elements such as spandrels, parapets, wall to pier joints, floor slabs and interior walls do not require strengthening. For the roof diaphragm and framing, conclusions were similar to those described for Sage Hall.

Portico Columns: The 1160-mm (46”) diameter plain concrete portico columns on the East elevation of Gould Hall have their calculated capacities larger than the earthquake demands regarding shear forces, biaxial bending moments, and their interaction with the axial loads. The cracking strength of the concrete is not exceeded by the earthquake loads on the columns. Although the unbraced length of the portico columns is rather large, they have massive cross-sections and do not provide support at floor levels like the columns of the building interior frames. This keeps the D/C ratios below 1.0 for the portico columns.

4. Scope of Retrofit Work

The seismic retrofit work envisioned for both Sage and Gould Hall involves strengthening the perimeter walls to increase their in-plane bending and shear capacities using sheet(s) of Carbon Fiber Reinforced Polymer (CFRP) fabric attached to the interior and exterior faces of the wall piers with epoxy. Glass or aramid FRP fabrics are not recommended for this application. The carbon fibers in the CFRP fabric are unidirectional, and therefore the fabric provides tensile strength along only one direction. Thus, the proper orientation of the fibers is essential. The CFRP fabric is to be oriented vertically on the pier jambs to provide extra in-plane bending capacity to the wall piers, and horizontally on the pier surface to provide extra in-plane shear capacity to the wall piers. In addition, the top and bottom ends of the vertical fabric are to be anchored into the pier-to-spandrel joints using CFRP anchors in order to develop the tensile strength of the vertical fibers into the joints. The CFRP anchors are to be epoxied into predrilled holes in the pier jambs where the vertical CFRP fabric will be located.

A single layer of CFRP fabric is 1 mm (0.04”) thick, (305 mm) 12” or (610 mm) 24” wide, and is epoxy adhered to the prepared concrete wall surface. Additional layers of CFRP fabric can be epoxied on to the first layer to provide additional strength. The number of layers of CFRP fabric required to provide specifically indicated additional capacity was determined based on the equations of the FRP design guide ACI 440.2R-02 (2005). The perimeter wall piers in the building transverse (North-South) direction require the most number of layers or the largest amounts of CFRP fabric per square meter (foot) of wall surface. For a two-sided application of horizontal CFRP (i.e. only on the exterior and interior faces of a pier), some of the piers in the building transverse direction require 10 or more layers of fabric, which is not feasible. These piers must be fully wrapped with the CFRP fabric, which requires removal and replacement of the window framings on either side of these piers. A third option for the placement of the horizontal CFRP fabric is the two-sided application with CFRP anchors. In this option, the horizontal CFRP fabric is epoxied to the exterior and interior faces of a pier, and the horizontal fabric on each face is tied together by the CFRP anchors. This requires predrilling of holes through the thickness of the pier to epoxy-place the anchors in the holes. The CFRP anchors are to be located at each end of a 12” or 24” wide band of CFRP fabric. This third option has the benefit of using the fewer number of fabric layers of the fully-wrapped application in a two-sided application, and avoids removal and replacement of window frames.

Similar to horizontal CFRP, some of the perimeter wall piers, especially those in the building transverse direction need too many layers of vertical CFRP fabric for application on pier jambs only. Alternatively, fewer layers of vertical fabric are appropriate provided that the fabric is placed on the jambs and continued on the interior pier face for a horizontal distance of 600mm (2ft) from the jambs.

The implementation and detailing of the seismic retrofit was prepared after careful consideration of the architectural features, structural details, and mechanical components of the building that were determined during our field investigation. The typical arrangement for the installation of the CFRP is shown in Figure 5.

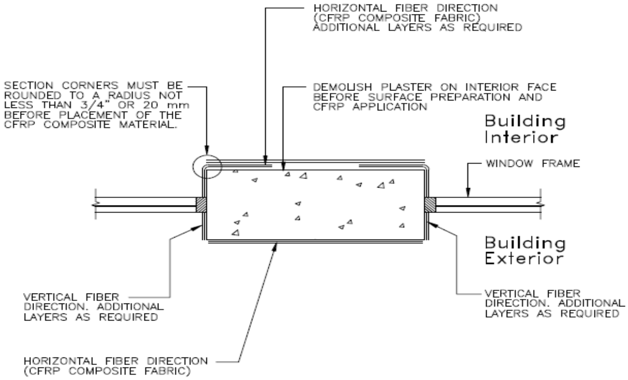

Figure 5

5. Conclusions

Our investigation was performed as part of a feasibility study for the voluntary seismic upgrade considered by the College authorities for the Sage and Gould Hall buildings. A wealth of information was obtained from documents regarding the Robert College site, soil properties, and in particular the Sage Hall and Gould Hall buildings. Seismic hazard was determined at the Robert College site, key issues pertaining to the seismic investigation and upgrade of Sage and Gould Halls were identified, and retrofit strategies were developed for the two buildings.

Seismic risk for Sage and Gould Halls was assessed and determined to have 36% probability of experiencing moderate structural damage, and 38% probability of non-structural acceleration sensitive damage from a code basis design level earthquake. The expected value of structural damage is 11% of the building value, and 16% for the non-structural acceleration sensitive damage.

We performed detailed structural engineering analyses for both Sage Hall and Gould Hall in order to identify the deficiencies in the buildings' lateral force resisting systems. We determined that the unreinforced concrete perimeter wall piers in both buildings are particularly vulnerable to seismic forces in the walls' in-plane direction. Our investigation showed that both Sage and Gould Hall buildings require structural strengthening in order to provide life safety protection to the occupants in the event of a code-level earthquake. Our proposed strengthening technique employs the use of CFRP composite fabrics and anchors on the interior, exterior, and jamb faces of the buildings' perimeter wall piers, while utilizing the existing structural system of the buildings. Compared to alternative retrofit methods, the CFRP application will be less invasive and less disruptive for the occupants, and more successful in conserving the functionality, architecture and heritage of the College.

The retrofit implementation scheme was detailed and shown to have very little effect on the mechanical systems of the buildings. Cost is expected to be minimal with regards to the mechanical systems within the scope of the proposed retrofit work. This retrofit plan also minimizes impact on the architecture by strategically placing the CFRP fabrics on the wall piers that have surface offsets and undulations, and selecting a finish material that allows the CFRP fabrics to blend in with the rest of the bare concrete wall surfaces.

Our proposed retrofit work may require emptying out parts of the building, in particular the rooms along the perimeter of the building, at various times in order to carry out the retrofit work on the interior faces of the perimeter wall piers. Work on the exterior (erecting scaffolding and applying CFRP fabric) does not interfere with functions inside the building. Drilling of holes to insert CFRP anchors into the perimeter wall piers, and demolition of the interior plaster is expected to cause some noise pollution.

Regarding phasing of the work, we recommend that the CFRP retrofitting begin with Gould Hall first where the perimeter wall piers have been determined to fail in shear (a more serious form of failure) as opposed to flexure that is expected for the wall piers in Sage Hall. We also recommend that the wall piers in the buildings' transverse (short) elevations be retrofitted first where the wall piers are most vulnerable due to large D/C ratios. Furthermore, it will be cost effective if the retrofitting is performed story by story as the architectural features such as string-courses (and correspondingly the placement of the CFRP fabrics) vary from one story to the next. Each story can be retrofitted at different times but the cost of assembling and dismantling the scaffolding and staging the construction crew and material has to be factored into the work phasing decision. Finally, we recommend retrofitting the exterior and interior faces of the same wall pier at the same time. This achieves proper CFRP installation and better confinement for the wall pier, and when working from the inside, allows access to the wall pier from the outside while the exterior scaffolding is still in place. Moreover, retrofitting of the wall pier is effective only when both the interior and exterior surfaces of the wall piers have been retrofitted with CFRP. It is anticipated that the surface preparation prior to application of the CFRP will take considerably more time than the application itself. A detailed phasing plan can be developed in conjunction with a contractor familiar with local labor and material availability keeping in mind the College's constraints.

The analyses and evaluation presented in this report focus not only on the structural and material aspects of a retrofit design application but also the architectural aspects of such an undertaking at the Sage and Gould Hall buildings of Robert College. This multidisciplinary collaboration makes this comprehensive report possible.

The major architectural objective in this process can be defined as preserving the already existing architectural values by assisting the structural decisions. Only the awareness of these values makes it possible to produce retrofit solutions of similar or higher quality. The CFRP fabric which is proposed as the primary retrofitting material offers a simple and flexible application process with the least amount of impact on the architecture of the buildings when compared to other materials or techniques. However, professional and disciplined execution is a must at all phases of the retrofit application as with other materials or techniques.

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