# INNOVATIVE RETROFIT OF A HERITAGE BUILDING REAL CASE USING FRP TECHNOLOGY AND STEEL JACKETING

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**Abstract** - In this paper evaluation of seismic capacity of a historical building is carried out. It had been used as a national library about 40 years ago. Also, before that, it had been constructed as a part of a Royal complex. This building has been constructed by traditional methods using bricks and mortars. The ceilings system of the structure consists of jack arches. Also, the roof of the building has been constructed with wood trusses. The building does not have any designed lateral bearing system. Lateral resistant of the building is due to masonry walls and due to brittle and non-ductile performance of it. In secondary cycles of earthquake vibration, it will loose its stiffness and strengthening radically. Also the building does not have any reliable about integrity. Load bearing systems are not reliable too. In this paper the evaluation of resistant capacity of the building is established and the weak points of the system are distinguished. For some masonry columns some traditional method of steel jacketing is designed and for increasing the reliability of the columns, FRP sheets are applied. In order to retrofits the walls, FRP sheets are installed on its surfaces, the externally bonded FRP sheets are strengthening the wall against in-plane and out of plane applied horizontal forces. Combination of the steel jacketing and externally bonded FRP sheets is prescribed to achieve an integrated system of the elements.

**Keywords** - URM, masonry, retrofit, historical building, FRP

## I. INTRODUCTION

In recent years, traditional methods for building design based on designing procedure for new building to obtain earthquake resistant structure has been reviewed and re-investigated. Major differences in this review have been change the method of "strength" to method of "performance". Before, strength and performance had been used in same definition, but recently, it has been proved that increases of strength don't increase the safety of the structure and don't reduce damages.

The terminology used for target Building Performance Levels is intended to represent goals of design. The actual ground motion will seldom be comparable to that specified in the Rehabilitation Objective, so in most events, designs targeted at various damage states may only determine relative performance. Even given a ground motion similar to that specified in the Rehabilitation Objective and used in design, variations from stated performance objectives should be expected and compliance should not be considered a guarantee of performance. Variations in actual performance could be associated with unknown geometry and member sizes in existing buildings, deterioration of materials, incomplete site data, variation of ground motion that can occur within a small area, and incomplete knowledge and simplifications related to modeling and analysis. Information on the expected reliability of achieving various target Building Performance Levels when the requirements are followed can be found in standards. [1-4]. It is expected that most buildings rehabilitated in accordance with performance based design would perform within the desired levels when subjected to the design earthquakes. The practice of earthquake engineering is rapidly evolving, and both our understanding of the behavior of buildings subjected to strong earthquakes and our ability to predict this behavior are advancing. In the future, new knowledge and technology will provide more reliable methods of accomplishing these goals.

New building codes are primarily intended to regulate the design and construction of new buildings; as such, they include many provisions that encourage the development of designs with features important for good seismic performance, including regular configuration, structural continuity, ductile detailing, and materials of appropriate quality. Many existing buildings were designed and constructed without these features and contain characteristics such as unfavorable configuration and poor detailing that preclude application of building code provisions for their seismic rehabilitation. Historically, criteria for evaluation have been set lower than those for design to minimize the need to strengthen buildings that would otherwise have only modest deficiencies. The expertise of the design professional in earthquake engineering is an important prerequisite for the appropriate use of retrofit standards in assisting a building owner to select voluntary seismic criteria or to design and analyze seismic rehabilitation projects.[5,6]
In this paper evaluation of seismic capacity of a historical building is carried out. It had been used as a national library about 40 years ago. Also, before that, it had been constructed as a part of a Royal complex. In this paper the evaluation of resistant capacity of the building is established and the weak points of the system are distinguished.

## II. BUILDING DESCRIPTION

This building has been constructed by traditional methods using bricks and mortars. The ceilings system of the structure consists of jack arches. Also, the roof of the building has been constructed with wood trusses. The building does not have any designed lateral bearing system. Lateral resistant of the building is due to masonry walls and due to brittle and non-ductile performance of it. In secondary cycles of earthquake vibration, it will lose its stiffness and strengthening radically. Also the building does not have any reliable about integrity. Load bearing systems are not reliable too.

This building had been designed and constructed in 1928. All of the gravitas weight loads are carried out by bricks and mortars. Floors weights have been supported by jack arches. The structure of building roof is wood trusses that are covered by galvanized steel plates.

**Table 1- building specifications**

| | | |
|---|---|---|
| Structure | brick walls and clay mortar | |
| Plan Dimensions | 27.75x22.75 | m |
| Story number | 3 | m |
| Total plan surface | 1895 | m2 |
| application | Library and amphitheaters | |
| Base level | -0.7 | m |
| Story levels | 5.15, 4.25, 3.55 | m |
| Roof level | 13.75 | m |
| Foundation | Unknown | |
| Floors | Jack Arches + wood trusses | |
| Soil type | II | |




**Figure 1- building pictures**

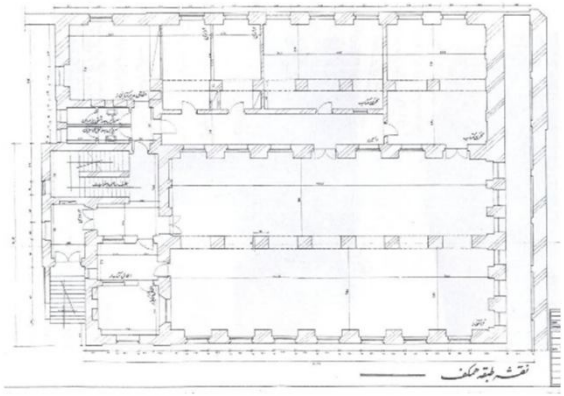


**Figure 2- plan of the building**

## III. DEFINITION OF REHABILITATION OBJECTIVE

The Rehabilitation Objective selected as a basis for design will determine, to a great extent, the cost and feasibility of any rehabilitation project, as well as the benefit to be obtained in terms of improved safety, reduction in property damage, and interruption of use in the event of future earthquakes. Figure 3 indicates the range of Rehabilitation Objectives that may be used.

Operational Performance, Immediate Occupancy Performance, Life Safety Performance, Collapse Prevention Performance are levels of rehabilitation. For this building the Operational (1-A) with properties: Backup utility services maintain functions; very little damage, is selected because of its high important and historical.

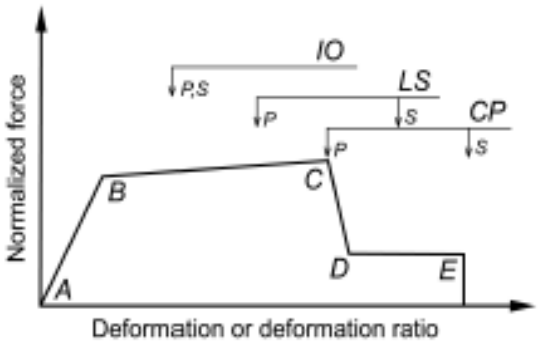



**Figure 3- force versus deformation ratio and rehabilitation levels**

**Table 2- earthquake hazards- maximum acceleration, velocity and displacement due to earthquake**

| period (years) | A(m/s$^2$) | A(g) | V(cm/s) | D(cm) | F (d=2%) | F (d=5%) |
|---|---|---|---|---|---|---|
| 225 | 2/57 | 0/262 | 0/241 | 0/136 | 2.739 | 2.116 |
| 475 | 3/49 | 0/356 | 0/327 | 0/184 | 2.026 | 1.650 |
| 2475 | 5/50 | 0/560 | 0/600 | 0/336 | 1.633 | 1.385 |

## IV. EARTHQUAKE HAZARDS

Risk analysis of earthquake hazards have been performed for local position of building and the results shows different values for maximum estimated Peak Ground Accelerations. The PGA for different return periods are given in Table 2.Spectral values for acceleration, displacement and velocity, F,are in two last columns of Table 2. It has been given by Equation 1, in which, $S_a$, is Spectral Acceleration:

$$S_a=F_a.A \quad (1)$$

Spectral velocity and displacement can be obtained in same approach.

## V. ANALYSIS PROCESS

All of Steels that use in this building are ST37, by minimum yielding stress 2400 kg/cm2 and 3700 kg/cm2 ultimate stress. Compressive strength of bricks is 50 kg/cm2 based on experimental tests and shear resistant of mortars have been obtained by averaging between 9 numbers of tests in each story. These values are displayed in Table 3.Slab details of each floor are given in Table 4. Density and weight of each component is measured and calculated. Summation of gravity loading of each square meter of floors is 610 kg.

**Table 3- experimental results of mortars test**

| Story | Shear strength of mortars(kg/cm2) |
|---|---|
| Under ground | 2.4 |
| Ground | 1.9 |
| First | 1.5 |

**Table 4- slab details**

| materials | thickness | density | weight |
|---|---|---|---|
| finishing | 0.02 | 2100 $Kg/M^3$ | 0.02*2100=41 $Kg/M^2$ |
| mortars | 0.02 | 2100 $Kg/M^3$ | 0.02*2100=41 $Kg/M^2$ |
| jack arch | 0.23 | 1850 $Kg/M^3$ | 0.23*1850=425 $Kg/M^2$ |
| beams | - | - | 100 $Kg/M^2$ |

Equation 2 describes pseudo static method to calculate the base shear in terms of building parameters. This method is used in codes based on building weight.

$$V=C.W \quad (2)$$

In which, V: base shear, W: building weight, C= f (A, B, I, R), A: intensity of acceleration, B: response factor, I: important factor, R: Behavior factor, these factors are different in various CODES, but C factor almost obtained the same value. Some of building codes assume that:

$$C=\frac{ABI}{R} \quad (3)$$

Where: $B=2.5(\frac{T_0}{T})^{\frac{2}{3}}$ (4)

$$T=0.07H^{\frac{3}{4}} \quad (5)$$

$$T_0=0.5 \quad (6)$$

$$A=0.35 \quad (7)$$

$$F_i=(V-F_t)\frac{W_ih_i}{\sum_{j=1}^{n}w_jh_j},\ F_t=0.07TV$$

Seismic specification of building due to existing codes is calculated in table 5. Period of structure is 0.35 seconds, and the base shear of building is 640 ton. Each story shear can be calculated by normal distributing model as a triangular distributing is presented in Table 6. Based on shear resistant of mortars and bricks, shear resistant of each walls of building can be calculated and after summation in each directions is presented in Table 7.

**Table 5-seismic specification**

| A | B | I | R | Te | $T_0$ | $T_S$ |
|---|---|---|---|---|---|---|
| 0.35 | 2.5 | 1.2 | 4 | 0.35 | 0.1 | 0.5 |
| V(ton) | C | $W_{DL}$ | $W_{LL}$ | We | V(ton) | |
| 640 | 0.26 | 2025 | 725 | 2460 | 640 | |

**Table 6- base shear and story shears**

| Story | Dead load | Live load | surface | Wall Length | Dead W. | Live W. | Wall w. | Fi | Vi |
|---|---|---|---|---|---|---|---|---|---|
| First | 300 | 150 | 631 | 156 | 189.3 | 94.65 | 288.6 | 249 | 249 |
| Ground | 610 | 500 | 631 | 210 | 384.91 | 315.5 | 388.5 | 269 | 518 |
| Under G. | 610 | 500 | 631 | 210 | 384.91 | 315.5 | 388.5 | 122 | 640 |
| Sum. | | | | | 959.12 | 725.65 | 1065.6 | 640 | |

**Table 7- shear resistant of walls**

| Story | South-North Wall length | East-West Wall length | Wall Width | Shear strength of mortars(kg/cm2) | S-N-wall Shear resistant(ton) | E-W-wall Shear resistant (ton) | Earth quake shear (ton) |
|---|---|---|---|---|---|---|---|
| First | 75 | 81 | 1 | 1.5 | 1125 | 1215 | 249 |
| Ground | 75 | 135 | 1 | 1.9 | 1425 | 2565 | 518 |
| Under G. | 75 | 135 | 1 | 2.4 | 1800 | 3240 | 640 |

Based on FEMA codes the base shear, V, is calculated by Equation 8:

$$V=0.33AIW \quad (8)$$

Story shears, $V_i$, can be obtained by driving $V_i$ and $A_i$, total section surface of story walls(with thickness over 200 mm), the sections should be considered without opening length and only walls by length greater than 1/6 summation length of openings or 2/3 height of smaller opening.[7-8]

$$A_i=\frac{V_i}{V_a} \quad (9)$$

Allowable shear stress, $V_a$, can be calculated by Equation below, in which maximum $V_1$ is 6 kg per square:

$$V_a=0.1V_1+0.15\sigma_C \quad (10)$$

Based on this calculation each wall has a special specification that is presented in Table 8. Base shear and story shear based on FEMA 356 is displayed in

Table 9.

Relative walls calculation shows in Table 10 indicates that building have a good ratio of this value and is safe about these criteria. Shear stress of walls is presented in Table 11 and the values of stress are less than allowable stress obtained by result of test.

**Table 8- seismic specifications of walls**

| A | I | We | $W_{DL}$ | $W_{LL}$ | We | Vton |
|---|---|---|---|---|---|---|
| 0.35 | 1.2 | 2460 | 2025 | 725 | 2460 | 341 |

**Table 9- base shear and story shears based on FEMA356**

| Story | Dead load | Live load | surface | Wall Length | Dead W. | Live W. | Wall w. | Fi | Vi |
|---|---|---|---|---|---|---|---|---|---|
| First | 300 | 150 | 631 | 156 | 189 | 95 | 289 | 133 | 133 |
| Ground | 610 | 500 | 631 | 210 | 385 | 316 | 389 | 143 | 521 |
| Under G. | 610 | 500 | 631 | 210 | 385 | 316 | 389 | 65 | 341 |

**Table 10- relative walls calculations**

| Story | South-North Wall length | East-West Wall length | Wall Width | Story surface (m2) | S-N relative walls(m) | W-E relative walls(m) |
|---|---|---|---|---|---|---|
| First | 75 | 81 | 1 | 631 | 0.12 | 0.13 |
| Ground | 75 | 135 | 1 | 631 | 0.12 | 0.21 |
| Under G. | 75 | 135 | 1 | 631 | 0.12 | 0.21 |

**Table 11- shear stress of walls(kg/cm2)**

| Story | South-North Wall length | East-West Wall length | Wall Width | Vi(ton) | S-N Wall Shear Stress | W-E Wall Shear Stress |
|---|---|---|---|---|---|---|
| First | 75 | 81 | 1 | 133 | 0.18 | 0.16 |
| Ground | 75 | 135 | 1 | 521 | 0.69 | 0.39 |
| Under G. | 75 | 135 | 1 | 341 | 0.45 | 0.25 |

Nonlinear static analysis has been performed to analyzing the structure of the system and the target displacement obtained by Equation 11 as below [8]:

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g \qquad (11)$$

Coefficients are presented in FEMA356 Codes [9-11]. Building performance is a combination of the performance of both structural and nonstructural components. On average, the expected damage would be less. For comparative purposes, the estimated performance of a new building subjected to the 2475 years return period level of shaking is indicated.

The acceptability of force and deformation actions shall be evaluated for each component in accordance with the requirements of Section 3.4 of FEMA. Each action shall be classified as deformation-controlled (ductile) or force-controlled (non-ductile.The rehabilitated building shall be provided with at least one continuous load path to transfer seismic forces, induced by ground motion in any direction, from the point of application to the final point of resistance.

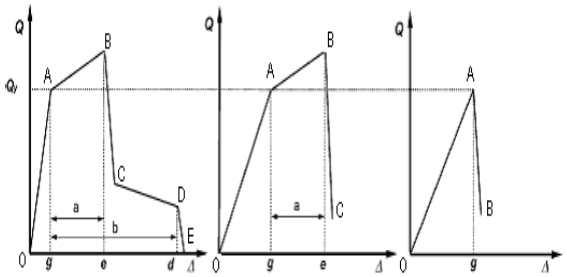



**Figure 4- acceptance criteria for various structures**

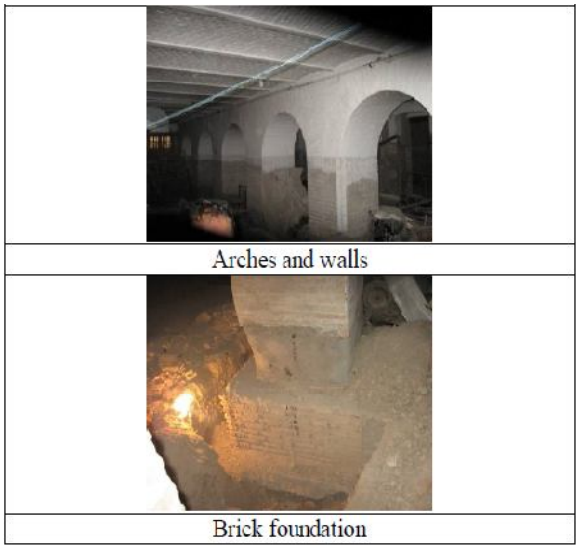



**Figure 5- foundation and walls detail**

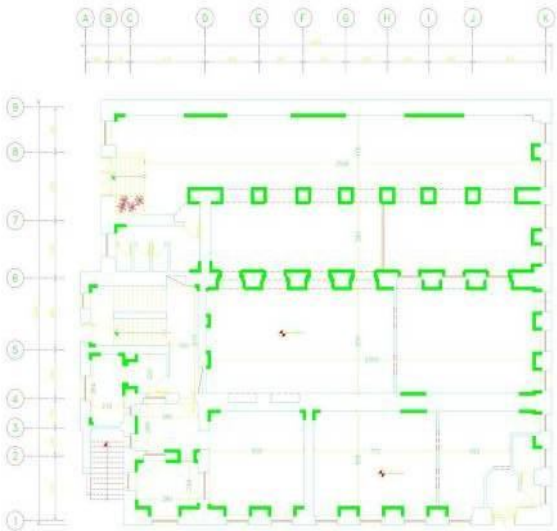


**Figure 6- rehabilitated slabs (left hand), walls and columns with FRP (green lines in right hand)**

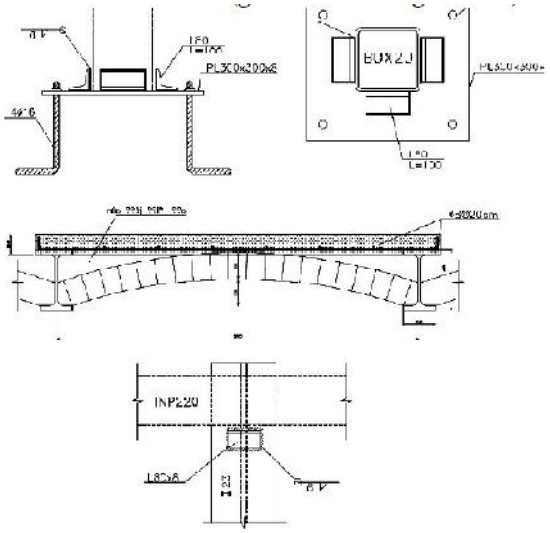



**Figure 7 – vertical and horizontal tie beams**

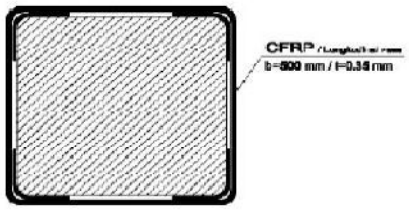
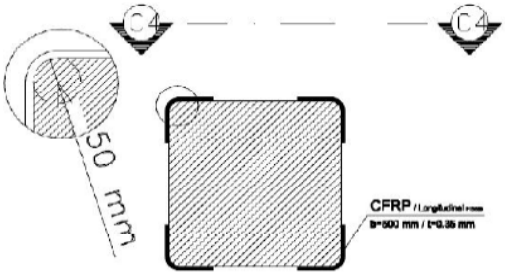



**Figure 8- connection detail of ties**

## VI. REHABILITATION STRATEGY

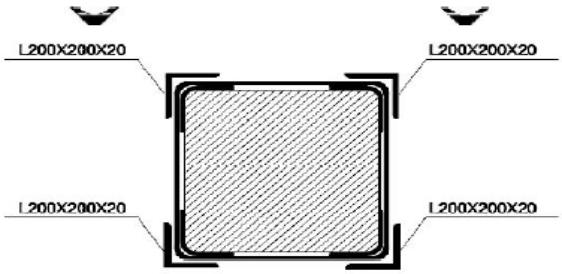
This building has some problems that are listed below and can be seen in Figure 5. Structural Irregularity and component Consistency of the building has poor. The structural system needs more consistency system to make a good resistant and integrative structure. The building has not any Secondary system to be safe in shakes. Foundation of system is very poor and don't has tie beams between foots.

Height of walls in this building is very tall and it needs to be tied at semi level of height. Also, free length of walls is too long and needs to be established supporting by tie columns as be designed. Distance between opening and wall edges is too small; it should be retrofitted by appropriate approach. Tie beams over walls need to give integrity between walls and roofs. Floors slabs and its stiffness are not complete and it should be braced in horizontal plane. For improving this properties it should be considered that the path of loads will be completed are better material quality. Using better quality of materials could be helping the building to be safe in resistant of loads.




RETROFITTING - STEP 1/4
COLUMN:C4

RETROFITTING - STEP 2/4
COLUMN:C4

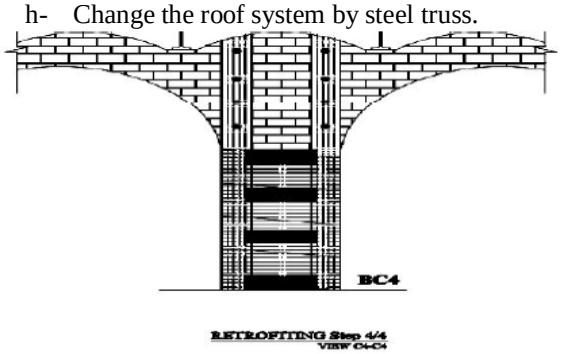


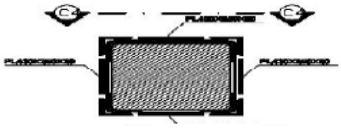

RETROFITTING - STEP 3/4
COLUMN:C4

**Figure 9- detail for retrofit of columns**

To obtain these goals this approach has been designed:

a- Retrofit of foundation
b- Steel jacketing of columns (Figure 10) after FRP confined
c- FRP confinement of walls and columns (Figure 6)
d- Tie beams, vertically and horizontally (Figure 7)
e- Retrofit of opening by FRP sheets in around
f- Make a rigid slab with horizontal bracing and added concrete slab (Figure 6).
g- Bracing the short towers on the roof.
h- Change the roof system by steel truss.



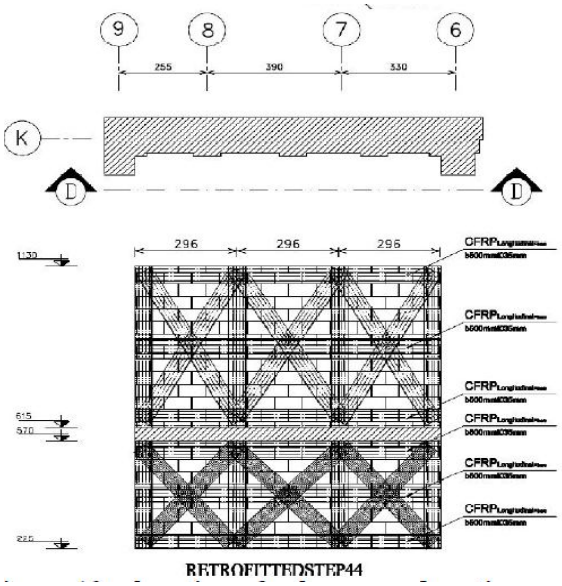



**Figure 10- elevation of columns and sections**

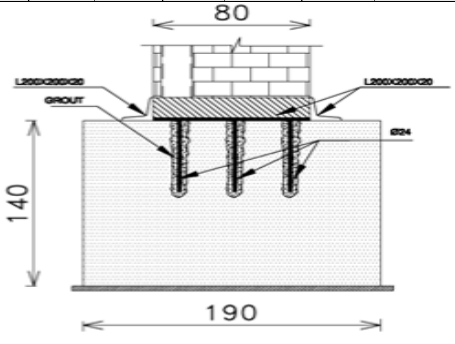
**Figure 11- FRP bracing on walls**

Resistant of brick-mortars walls will be reduced after first cycles of earthquake and after initial cracks, so the FRP sheets can be reduced the walls drifts and make a higher integrity after first cycles of shakes.This FRP sheets that are used in this sketched have below specifications:

$F_y$=3000 MPa , E= 600 GPa, thickness= 0.35 mm, Ultimate strain of FRP=0.04, Maximum strain of FRP under loading=0.04*816.4/3000, Maximum allowable drift =0.01, Maximum-lateral drift(angle=60deg.)=0.005.

**Table 12- result of analysis**

| Wall-story | Wall shear (Ton) | Total Wall shear( Ton) | Wall length (m) | Wall thickness(m) | Shear stress ($kg/cm^2$) | Allowable Shear stress ($kg/cm^2$) |
|---|---|---|---|---|---|---|
| E-W-STORY 3 | 1.41 | 1.41 | 7.40 | 0.90 | 0.002 | 1.5 |
| E-W-STORY 2 | 2.28 | 3.69 | 7.40 | 0.90 | 0.055 | 1.9 |
| E-W-STORY 1 | 1.48 | 5.17 | 7.40 | 0.90 | 0.077 | 2.4 |
| N-S-STORY 3 | 0.50 | 0.50 | 6.10 | 0.90 | 0.009 | 1.5 |
| N-S-STORY 2 | 2.00 | 2.50 | 6.10 | 0.90 | 0.046 | 1.9 |
| N-S-STORY 1 | 2.50 | 5.00 | 6.10 | 0.90 | 0.091 | 2.4 |



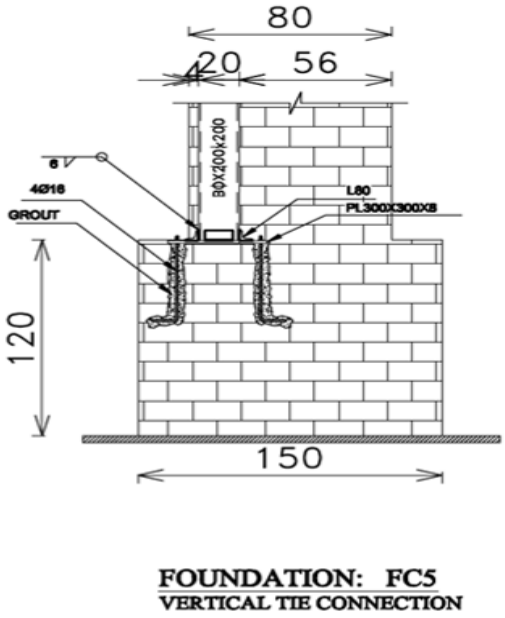




**Figure 12 – foundation confinement**

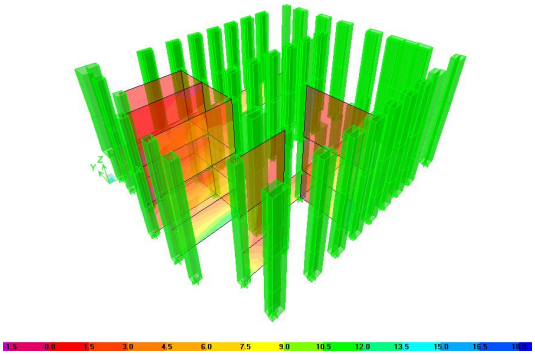


**Figure 13- modal deformation of structure**

**Figure 14- stresses result of analysis under lateral loading**

So the FRP sheets can cover all supporting forces to improving the wall specifications to reduce drifts and make a good safety up to don't appears any cracks for complete the structure as a good special rehabilitated building under high level of earthquake vibration. Results in analysis show that stress after rehabilitation is reduced in walls, and integrity of the system leads it to be a complete system with excellent distributing of lateral forces. Figure 13 is modal deformation of structure that improved and gets higher value in compare with existing building. Figure 14 shows that stresses is reduced by this FRP bounding up to 50 percent, this strategy of rehabilitation constrains the drifts and cracks during shakes, and this purpose is very necessary for this historical building. FRP sheets and Steel jacketing make a more stiffened and ductile resistant system.

## CONCLUSIONS

This building has a special approach for retrofitting because of its special important and the constraint of keep the façade of building. Due to its old structural system, only gravity loads could be supported by

walls and system has not any lateral resistant system to earthquake shakes. Some advanced and custom method has been used together for make a consistent resistant system for the building. As it can be seen in the nonlinear analysis the structure of building that is retrofitted analyzed and has not any plastic hinges under 2475 years return period earthquake. So the building expected will be stable and without any structural cracks due to the earthquake with return period of 2475 years.

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