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Seismic Evaluation and Strengthening of a Heritage Masonry Building

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ABSTRACT: The Rajnivas Building in Pondicherry was built during 1766 to 1769 by the French establishment in India. It is a two storeyed unreinforced masonry building with contemporary architecture. The load bearing walls provide resistance to lateral loads. A seismic evaluation of the building was done based on the equivalent static method method of IS 1893: 2002. In the analysis, only the in-plane lateral load resistance of the walls was considered. Any out-of-plane lateral load resistance was neglected. The slabs were assumed to act as rigid diaphragms connecting the walls.

From the analysis it was observed that for thirteen percent of the walls, the shear stresses were exceeding the permissible value. It was concluded that the building needs seismic retrofit. Some strengthening measures for enhancing the structural integrity were suggested. This paper provides the methodology of the analysis and a summary of the results.

1 INTRODUCTION

There are several historic masonry buildings in India which are considered as heritage buildings. After the recent earthquakes, there is a consensus in the evaluation and strengthening of these buildings for seismic forces. These buildings may not be safe with respect to seismic forces, judged based on the up-gradation of seismic zones (IS 1893: 2002), lack of seismic design and deterioration of the material. The paper presents the methodology of the seismic evaluation of the Rajnivas Building in Pondicherry, a heritage building under the jurisdiction of Public Works Department (PWD), Pondicherry. The Rajnivas Building was built during 1766 to 1769 by the French establishment in India. At present it is the residence of the Lieutenant Governor of Pondicherry and several offices of the Govermnet of Pondicherry. The seismic evaluation of the building included data collection, condition assessment and a detailed analysis based on the equivalent static method of IS 1893: 2002.

2 DATA COLLECTION

To conduct a proper assessment of a building, it is necessary to collect the relevant data of the building through drawings, enquiry, design calculations (for engineered buildings) and soil investigation report (if any). For a historic building, the original drawings, design calculations and soil report are generally not available. In such a situation the data collection is based on the survey of the building. The survey includes the development of new drawings based on physical measurement, studying the contemporary architecture, the original method of construction and subsequent additions/alterations, identification of architectural features and non-structural components and soil investigation.

For the Rajnivas Building, the drawings and the geotechnical report were provided by the PWD, Pondicherry. The building is two storeyed, with load bearing unreinforced brick masonry walls laid out in two perpendicular directions. The thickness of the walls is 600 mm in both the storeys. The walls have large arched openings for doors. There is verandah along most of the periphery of the building. In the ground storey, there are wall segments with arched openings along the edge of the verandah. In the first storey, pairs of columns are provided along the edge of the verandah. The walls extend 1.8 m below the ground floor level and rest on the soil. There is no spread footing for the walls.

The ground floor is made of lime concrete slab resting on compacted sand fill. 'Madras terrace' slabs are provided in both the first floor and roof. The Madras terrace slabs are made of bricks supported on timber rafters and beams. There is lime concrete and floor finish over the bricks. The thickness of each slab is around 400 mm. In a portion of the roof above the banquet hall, a 150 mm thick jack arch concrete roof was added in around 1980. There are two water tanks on the roof and parapet along the edges of the roof. The summary of the data collection is given in Table 1.

Table 1 : Data sheet

Survey	
Visited building site	Yes
Structural drawings available	No
Architectural drawings available	Yes
Geotechnical report available	Yes
Liaison with the designer or builder	Not Applicable
Building Description	
Building name / number	Rajnivas Building
Address	Pondicherry
Year of construction and subsequent re-modelling if any	Constructed during 1766 to 1769
Owner	Government of Pondicherry
Usage	Residential cum official
Material used	Brick masonry with lime mortar
Number of storeys	2
Plan size (approximate)	48.76 m × 44.16 m
Building height	12.82 m (11.02 m above ground floor level + 1.8 m extended below ground floor level)
Photograph / sketch	Plan in Fig. 1
Exposure Condition	
Environment	Coastal
Deterioration noticed	Timber rafters were deteriorated
Geotechnical and geological data	
Type of soil	Sand with standard penetration count (N) = 22. It is considered medium soil as per IS 1893: 2002.
Seismic zone	II
History	
This building was subjected to tremors of the earthquake on 26th January, 2001, with the epicentre in Bhuj, Gujarat. There was an earthquake on 26th September, 2001, of magnitude 5.4 (Richter scale) whose epicenter was located at 40.7 km south-east of Pondicherry. There were mild tremors of the earthquake on 26th December, 2004, with the epicenter in Sumatra, Indonesia. The building survived the earthquakes with visible cracks in a few places.	

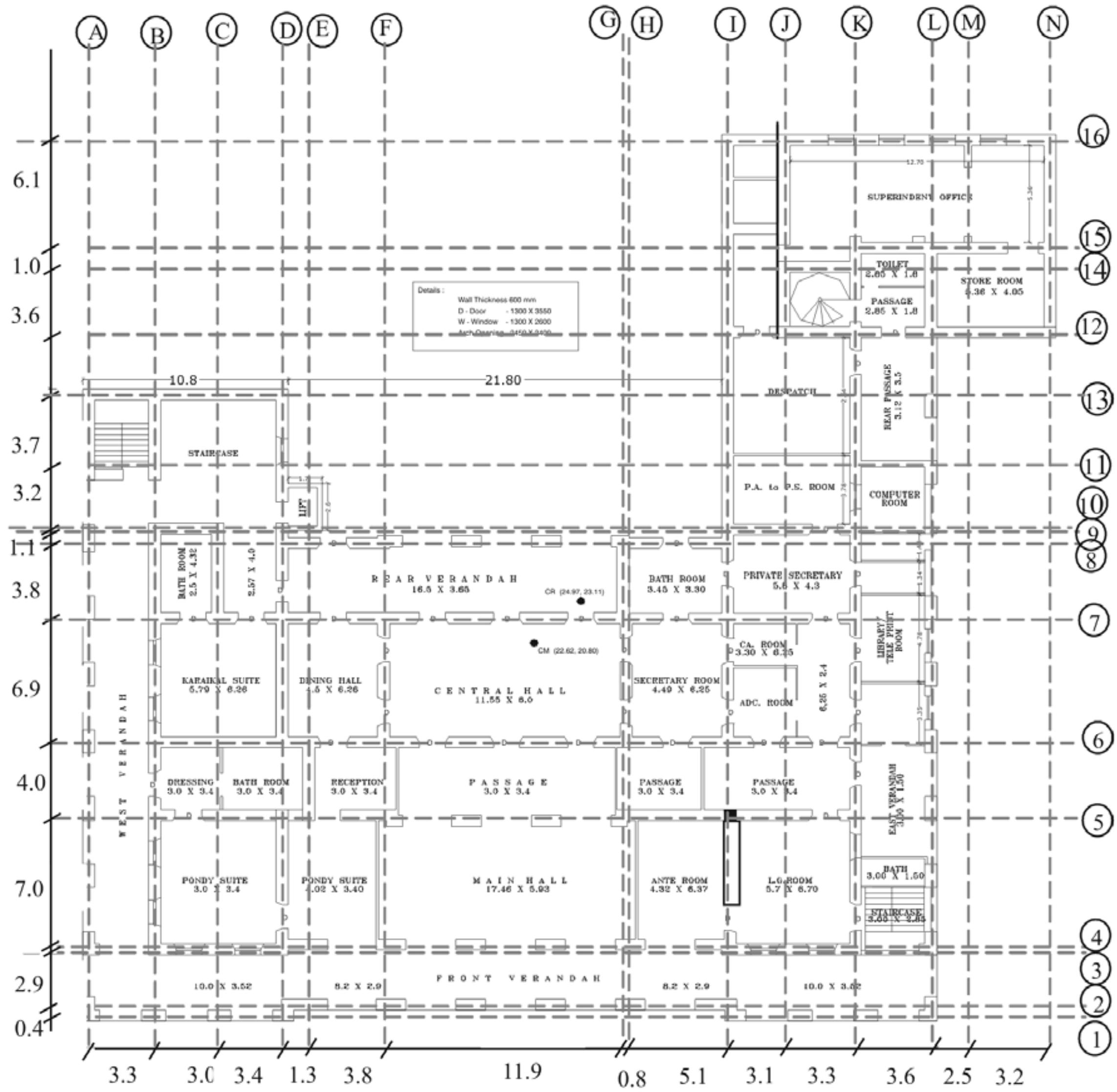


Figure 1 : Ground floor plan (all dimensions are in meters).

3 CONDITION ASSESSMENT

The condition assessment describes the process of assessing the actual condition of the structure in relation to its use. The objectives of condition assessment of an existing masonry building are as follows.

1. To obtain the properties of the structural materials used in the building.
2. To locate the deteriorated material and other defects, and identify their causes.
3. To detect any damage due to previous earthquakes.

A historic building needs condition assessment not just for seismic retrofit, but also for regular repair. For the Rajnivas Building an assessment of the arches and timber rafters supporting the slabs were undertaken by a team from College of Engineering Guindy, Anna University (Santhakumar 2002). Cracks were observed at a few end arches near the corners of the building. Some rafters had deteriorated due to termite infestation. It was suggested to replace the deteriorated rafters with steel joists.

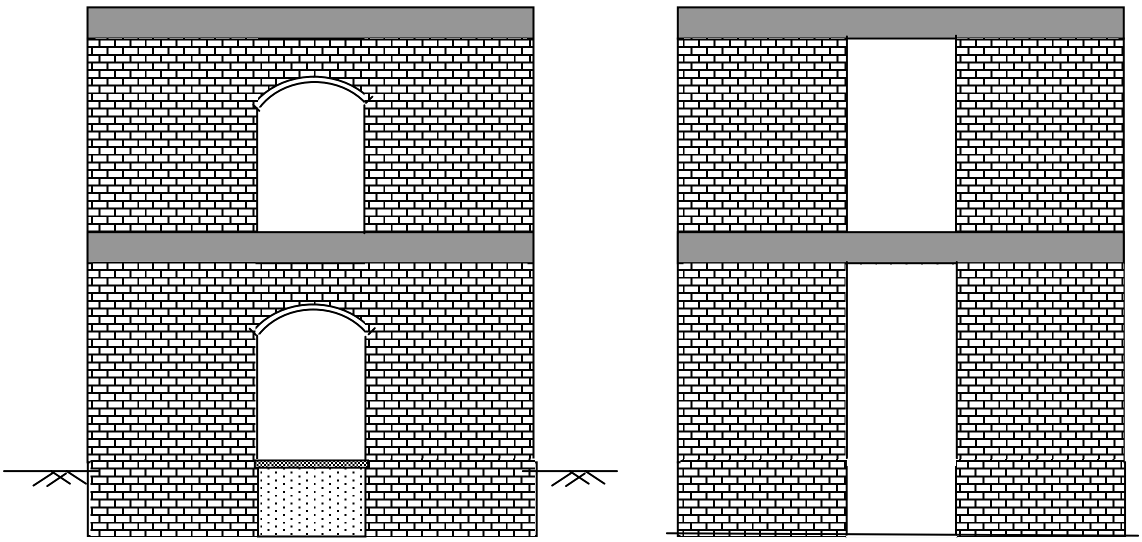
For the seismic retrofit it was necessary to determine the type and strength of the walls. It was not known whether the walls are made of bricks alone or there is some infill material in between the brick layers. Two horizontal core specimens (parallel to the bedding plane) were drilled out and it was confirmed that the walls are solid and made of bricks and lime mortar. The properties of the bricks were determined by testing the core specimens under uniaxial compression. The Compressive Strength and secant elastic modulus were 2.1 N/mm^2 and 998.0 N/mm^2 respectively. Any deterioration in the walls was not observed by visual inspection.

4 DETAILED ANALYSIS

4.1 Linear Static Analysis

4.1.1 Structural Model

The model for analysis of the building consisted of vertical wall segments (piers) resisting the seismic forces predominantly by shear. The portions of the walls above the doors, windows and arch openings were neglected. Any resistance of the columns along the periphery in the first storey was neglected. The slabs in the first floor and the roof were considered to act as rigid diaphragms. The interface of the slab and a wall was considered adequate for shear transfer. Neglecting the sand fill, the height of the ground storey was considered from the bottom of the wall. For in-plane stiffness, the ground storey walls were assumed to be pinned at the bottom and fixed at the first floor. The first storey walls were assumed to be fixed at both the first floor and roof. Any out-of-plane lateral load resistance of a wall was neglected. The seismic weight of the first floor included the weights of the walls of ground storey above mid height and those of the first storey below mid height. Similarly, the weight of the roof included the weights of the walls of the first storey above mid height, the parapet and the water tanks. A schematic representation of the model for each horizontal direction is shown in Fig. 2.



(a) Actual (b) Idealized model

Figure 2 : Model for analysis.

4.1.2 Method of Seismic Analysis

Since the building is regular with walls laid out in two perpendicular directions, the equivalent static method as per IS 1893: 2002 was considered to be adequate. The model for each direction is a two degree of freedom system. The time period for each direction was calculated by an eigen-value analysis of the model. The values came close to those calculated based on the empirical expression (Clause 7.6.2). The spectral acceleration coefficient for any value of the time period was governed by the constant horizontal portion of the response spectrum for medium soil.

The centre of mass (CM) for each floor was calculated based on the moment of the mass of each wall segment about a reference axis. The reference axes were considered to be parallel to the principle directions of the building. The centre of rigidity (CR) for each storey was calculated based on the moment of the in-plane stiffness of each wall segment about the reference axis. The stiffness of each wall segment is a series combination of the flexural stiffness and the shear stiffness. The values of stiffness can be calculated based on the boundary conditions, using standard expressions. The wall segments in a particular direction were assumed to act parallel. Hence, their stiffness values were added to get the total stiffness of the storey in the direction considered.

The design CM was shifted from the calculated CM based on Clause 7.9.2, IS 1893: 2002. The lateral force in each level was multiplied by the distance between the design CM and the CR to get the torsional moment in that level.

4.1.3 Checking for shear stresses

The shear force in a wall segment consists of two components. One is due to the direct shear and the other is due to the torsion. The direct shear force in the ith storey and jth wall segment is given as follows.

$$V_{Dj} = V_i \frac{k_j}{\sum k_j} \qquad (1)$$

Where V_i is the shear in the ith storey (summation of the lateral forces in the floors above) and k_j is the stiffness of the jth wall segment.

The shear force due to torsion in the ith storey and jth wall segment is given by the following equation.

$$V_{Tj} = M_i \frac{k_j r_j}{\sum k_j r_j^2} \qquad (2)$$

Where M_i is the torsional moment in ith storey (summation of the moments in the floors above) and r_j is the radial distance of the jth wall segment measured from the CR.

It was assumed that the failure in a wall can occur by sliding shear at the bed joint of the bricks. The shear stress (demand) in a wall segment was calculated from the total shear force in the wall segment. The shear stress was compared with the permissible shear stress (capacity). In absence of sliding shear test, the permissible shear stress was evaluated based on sliding failure as per IS: 1905: 1987 (Clause 5.4.3). The values of permissible shear stress for the ground and first storeys are 0.13 N/mm^2 and 0.11 N/mm^2, respectively.

A demand-to-capacity ratio (DCR) for each wall segment was calculated to compare the demand with the capacity. The DCR is defined as the ratio of the shear stress due to seismic forces and the permissible shear stress. It should be less than 1.0 for adequate strength. Fig. 3 shows the distribution of walls (in terms of percentage length of walls) with the values of DCR from the analysis.

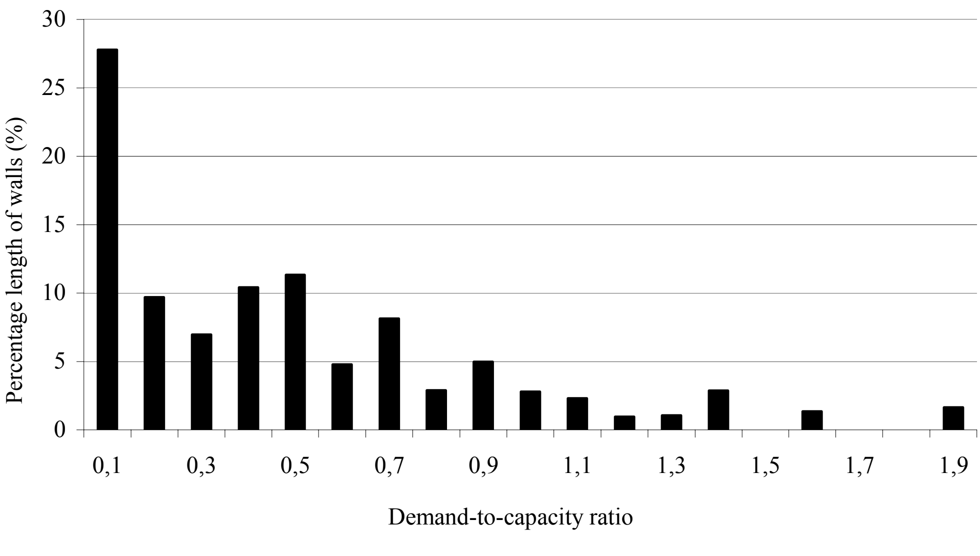


Figure 3 : Percentage length of walls versus demand-to-capacity ratio.

It is observed that due to the high thickness, most of the walls of the building are safe. About thirteen percent of the walls are exceeding the permissible shear stress. These walls are mostly in the ground storey. A global retrofit strategy can be designed based on strengthening a few primary walls such that the values of DCR are reduced. Local retrofit is necessary to strengthen the supports of the water tanks and the jack roof and to reduce the hazard from falling parapet.

4.2 Non-Linear Static Analysis

As an illustration for pushover analysis, a typical wall of the building was modeled as an equivalent frame (spandrel and pier model). Unlike in the model for linear static analysis, the portion of the walls above the doors and other openings were considered in the model. Each vertical wall segment was modeled by a column element. Each horizontal wall segment above an opening was modeled by a beam element. For the lateral load versus drift behavior of the frame, only the shear deformation of the wall segments was considered. Non-linear 'hinge' properties for shear deformation were defined for the two ends of each frame element. The shear hinge properties were calculated as per the recommendation of FEMA 273 (1997). From the analysis it was observed that shear hinges are forming in the ground storey walls.

5 SEISMIC STRENGTHENING

The following strengthening measures were suggested in addition to the regular repair works, to enhance the structural integrity of the building. These are immediate measures as compared to a comprehensive seismic retrofit.

1. Vertical and horizontal bands to be inserted to integrate the perpendicular walls at the corners.
2. Ties to be provided to integrate the slabs with the walls.
3. Horizontal hoop bars to be inserted at an edge of a wall next to an opening.
4. Cracked arches to be stitched with ties.

The bands, hoop bars and ties are to properly grouted. Fig. 4 shows the typical strengthening of a slab-to-wall connection. Fig. 5 shows the typical strengthening of a cracked arch and the provision of horizontal bands.

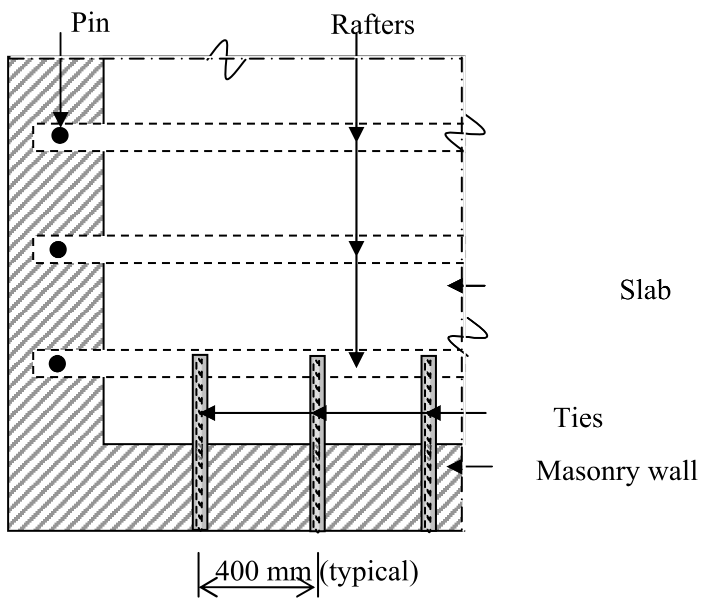


Figure 4 : Typical strengthening of a slab-to-wall connection at a corner.

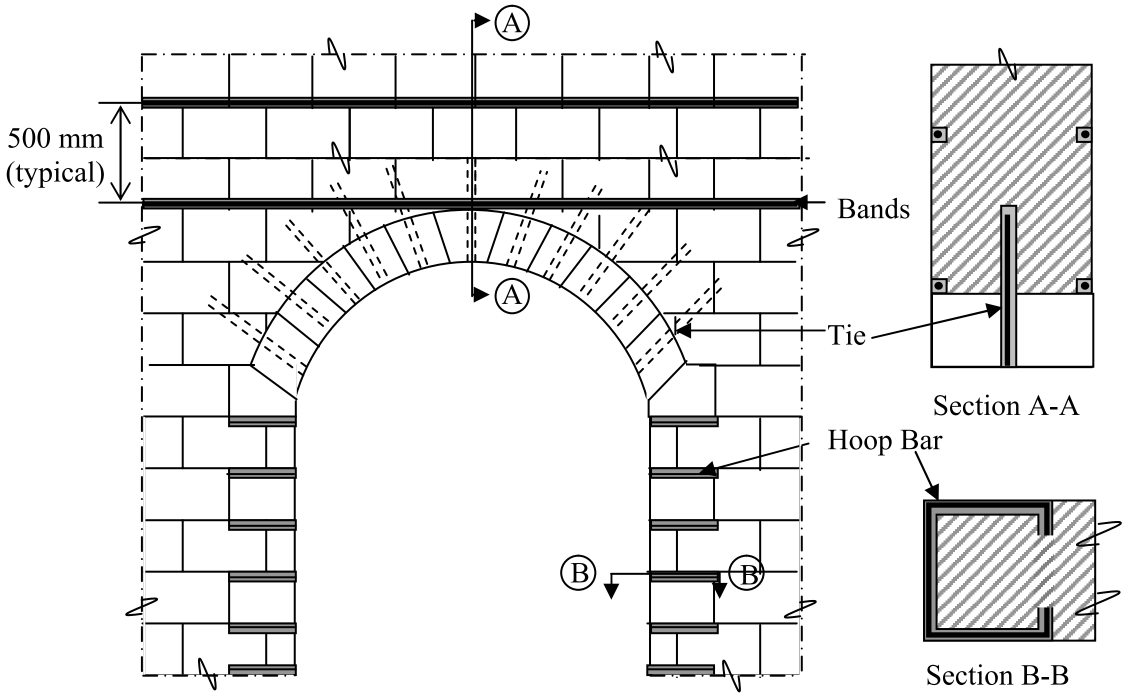


Figure 5 : Typical strengthening of cracked arches.

6 CONCLUSIONS

For a historic and heritage building in a seismic zone, other than regular repair, seismic retrofit is given importance. A seismic evaluation of a building is necessary before a retrofit programme is undertaken. This paper presents the methodology of seismic evaluation of a heritage masonry building. The steps of evaluation included data collection, condition assessment and a detailed analysis. The data collection is summarized in a table for easy reference. The testing of core specimens under condition assessment confirmed the type of wall and provided the material properties to be used in the detailed analysis. Based on the layout of the building, the equivalent static method was adopted for the analysis.

The procedures for calculating the centre of mass of a floor and the centre of rigidity of a storey are highlighted. Emphasis was laid in calculating the shear force in a wall segment due to the combination of direct shear and torsion. A demand-to-capacity ratio (DCR) was calculated for each wall segment. The values of DCR can be used to take a decision on seismic retrofit of the building, as well as to design an appropriate retrofit strategy. The strengthening measures are intended to increase the structural integrity of the building.

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