METHODOLOGY FOR STRENGTHENING AND REPAIR OF EARTHQUAKE DAMAGED MONUMENTS IN PAGAN - BURMA

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SUMMARY

This paper presents the methodology for strengthening and repair of momuments in Pagan, Burma. For development of an adequate method for repair and strengthening of the monument structures seismic studies and seismic hazard assessment as well as geophysical and soil investigations to define local soil conditions have been carried out. Also, determination of the dynamic characteristics of the monument structures was made. Considering the properties of the construction materials and the formulated representative mathematical models for structural dynamic response to expected seismic effects, based on defined seismic design criteria a methodology for repair and strengthening of this type of structures has been developed, and it will be presented in this paper.

INTRODUCTION

Repair and strengthening of historic monuments constructed in seismic regions, damaged either by earthquakes or to be strengthened during the restauration process, in order to protect them against future earthquakes, scientific and systematic approach towards protection of historical monuments is even more emphasized considering the specific character of this type of structures, such as brittle and nonductile construction materials, different types of structural systems, historical and artistic value of the monuments and their content, which imposes the need for definition of design criteria based on the seismic hazard and the defined seismic risk level, as a prerequisite for the study of the repair and strengthening methodology. The Pagan plateau, in the central part of Burma, is a world-wide known place by the high concentration of magnificent historic monuments, from the far past, like temples, and pagodas, unfortunately most of which have been severely damaged by natural disasters, including earthquakes.

The earthquake of 8 July 1975, with a magnitude of 6.8 destroyed or heavily damaged many monuments - tempels or pagodas. On the basis of the study of the neotectonic and seismotectonic characteristics of the wider Pagan region (where earthquakes with magnitudes up to 8 can be expected), and based on the methodology for probabilistic seismic hazard modelling, statistical analysis of earthquake data and selected attenuation relationships, seismic hazard data are presented in terms of peak ground acceleration for average soil conditions for return periods as follows : for a return period of 50 years, $a_{(g)}$= 240; return period of 100 years, $a_{(g)}$=300; for a return period of 500 years,

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a_m = 300; for a return period of 500 years $a_{(g)}$ = 460; and for a return period of 1000 years or maximum expected ground acceelration is $a_{(g)}$ = 530 cm/sec^2.

Based on the performed studies for determination of the seismic hazard, dynamic amplification factors of soil media, dynamic properties of structural systems obtained from field measurements, strength and deformability characteristics of structural materials, structural elements and entire structural systems, seismic design criterion and parameter have been determined. Two levels of design criteria based on economically justified damagibility and acceptable levels of seismic risk are established and used as follows: Level I criteria; for expected seismic effects, for a return period of 100 years and peak ground acceleration, $a_{(g)}$ = 300 cm/sec^2 the structures should work in elastic range without damage to structural elements with possible slight damage to secondary and non-structural elements. For this criteria level, applying EQA instead of PGA the equivalent seismic forces are determined through the shear base coefficient $K_{SE} \cong 0.30$. Level II-criteria; for expected seismic effects, for a return period of 500 years and peak ground acceleration of 460 cm/sec^2 structures can suffer damages which are technically and economically repairable. This criterion is met by control and limiting the deformability by dynamic response analysis for different types of earthquake records.

Considering, in general, that the structures of monuments in seismically active regions should not change the basic structural system by the process of repair and strengthening, and in particular, based on the performed dynamic field studies, developed seismic design criteria, and the dynamic response analysis of the monuments in the Pagan region, methods and techniques are developed in order to provide economically justified and technically consistent seismic safety with sufficient bearing and deformability capacity as well as an acceptable damage level in the future earthquakes.

DESCRIPTION OF THE TYPE OF STRUCTURES, BUILT-IN MATERIALS AND DYNAMIC PROPERTIES

The Pagan region is mainly characterized by two types of historical monuments, temples and pagodas (or stupas). The structural systems of the temple monuments consist of bearing massive walls combined with massive central pilars which form corridors or halls interconnected with domes or arches (Fig. 1 and 6, 7). The pagoda monuments are constructed as massive solid stupas with changeable form along the monument height (Fig. 2). It is important to be mentioned that large disproportion exists in respect to the size, both in temples and pagodas, starting from the impressive temples (Ananda, Gawdawpalin, etc.) up to 60 m high, and plan proportions from 50 to 60 m, to small one-storey temples of about 10 m in plan and height. All the monuments have been constructed in solid brick layed in mud mortar with or without plastering. The Institute of Technology from Rangoon, Burma, performed testing of the built-in material, both of bricks and masonry blocks (60 x 60 cm) in 6-7 monuments. The undisturbed samples were laboratory tested under compression and shear compression. The compressive strength of bricks is in the range f'_{BR} = (9.2 - 17.2) MP_a, while that of the masonry blocks is in the range of $f'_{M,B}$ = (1.72 - 3.55) MP_a, while it is concluded from the shear compressive test (τ_u, σ_o) that the tension bearing capacity of masonry

is very low, f_m = (0.02-0.025) MP_a. The general conclusion could be that the bricks are of good quality, while the low load carrying capacity is due to the poor bearing capacity of mortar. From experimental testing of dynamic properties of 16 selected monuments, applying the ambient vibration technique and the developed analytical models presented in Table 1, the following could be concluded: the elasticity modulus is within the range of M_{M1} (160-220) MP_a, the shear modulus G = (50-60) MP_a and the damping ratio c = (6-12%). The mode shape analysis, both experimental and analytical, pointed to the shear type behaviour of the lower rigid parts and bending type behaviour of the upper parts of the monuments. Basically, almost all selected monuments subject of experimental testing of the dynamic characteristics show that the structures are rigid with natural period in the range of T_1 = (0.15-0.57) sec., which is mainly due to the geometry and size of the monuments. Based on experimental measurements and analytically obtained values of selected monuments, as presented in Table 1, a relationship for definition of fundamental period of oscillation has been established as shown in Fig. 5, to be applied in the design, repair and strengthening of monuments.

Based on seismicity study of the central part of Burma and the expected earthquake effects in respect to ground acceleration and frequency content, the following representative ground accelerations of actual earthquakes were selected: El Centro N-S; Montenegro earthquake record in Ulcinj N-S, and Bucharest record N-S component, the normalized spectra of which have been shown in Fig. 3 as mean value envelopes. The normalized spectral values were used for definition of the proposed design response spectrum shown in Fig. 4. Based on the proposed spectrum (Fig. 4) the expressions for definition of the dynamic characteristics (Fig. 5) have been formulated, and stability criteria of structures established, to be used in the design of strengthened structures.

The analysis of damaged monuments, especially od selected representative monuments, taking into account their structural systems and characterictics of the built-in material points to the possible failure mechanisms; (i) loss of integrity of the structural system due to low tensile capacity of the masonry, occurrence of cracks of each story level and separation of the massive walls from the rigid central pillars or cores and independent working of each element proportional to the mass and the natural stiffness which prevents the force distribution proportional to the mass; (ii) failure or damage of tall and slender elements (shikaras) and the secondary decorating elements (corner stupas), see Fig. 1, due to amplified effects and the low bearing capacity, and (iii) shear failure in walls or the upper parts of supas (Fig. 3) due to the poor quality of mortar and the shear force resistance. Taking into account the above descibed modes of failure, the material properties and the structural systems, the dynamic characteristics and the expected possible earthquakes, the following method of strengthening and repair of monuments in Pagan has been proposed:

(i) Preserving of structural system integrity at each story level, by inserting of steel bracings, for small and medium size temples (Fig. 6) and/or by construction of reinforced concrete belt courses (Fig. 7) around the structure and at each story as defined by the free height of corridors and halls, in the case of medium size temples.

(ii) Strengthening of the upper slender parts of the monuments (shikaras) by inserting of horizontal R/C belt courses and injection of the massive

masonry for increasing of the shear load carrying capacity, and inserting of vertical RC belt courses to prevent bending failure (Figs. 6 and 7). In other words, these parts of the structure are repaired and strengthened in such a way to provide the required ductility and shear resistance capacity.

(iii) Strengthening of structural walls (massive and/or medium size) or central pillars is generally carried out by injection of the existing masonry by cement emulsion increasing thus the shear resistance capacity and the bending or tension effects. It should be pointed out that the analysis of the load carrying and deformational capacity of structural systems through equivalent mathematical models and calculations of load carrying capacities showed that in most cases, the seismic stability criteria of the structural systems satisfy the safety requirements if injection of masonry is applied (due to the massiveness, the size and the proper concept of the structural system) avoiding thus the conventional way of strengthening the masonry by construction of vertical RC columns or frames which in the case of massive sections proved to be ineffective due to their different bearing and deformational characteristics.

If in some cases it becomes necessary to increase the load carrying and deformational capacity of masonry, either of the entire structure or in some levels, then, the so called "jacketing" method is suggested in order to promote the confinement effect and increase the shear and bending capacity of walls or pillars.

Fig. 7 shows the example of Ananda temple, where sudden change in stiffness takes place at the third floor level. The nonlinear dynamic response analysis shows clearly that on the third floor level deformation accumulation and concentration takes place so that the central pillars have to be strengthened by jacketing and partial injection, while the massive horizontal reinforced concrete belt course will promote the structural integrity and a joint work of all the elements.

Because of the massive central pillars, RC belt courses are constructed around the massive walls of the lower floors, strengthening them by partial injection while the upper part (Fig. 7) should be strengthened by confinement of masonry with partial injection. The repair and strengthening of stupas is similar to that of temples - shikaras, that is, the upper parts are strengthened by vertical and horizontal R/C belts, while the lower parts by masonry and partial injection of the existing masonry.

Analysing the structures and their required stability from one side and the technically possible and economically justified method of repair, on the other, it was concluded that the most efficient method of repair and strengthening of the main system is the injection. This is the most efficient method in the case of good load carrying characteristics of the brick since it improved the bond characteristics and improves the bending and shear capacity of the structure, while by inserting, bracings and horizontal R/C belts, a good prerequisite has been established for an integral work of the structure and adequate effect distribution according to their stiffness and deformational characteristics.

CONCLUSIONS AND RECOMMENDATIONS

The repair and strengthening of historical monuments constructed in seismic zones should be carried out without introducing any changes or strengthening of the main structural systems.

The proposed method of strengthening by injection is one of the most acceptable ones, the improvement effects of the load carrying and deformational characteristics of which have also been proved experimentally. Due to different local characteristics of the built-in materials used for construction of temples, their experimental verification is suggested both from a viewpoint of definition of their basic characteristics and their economic justification.

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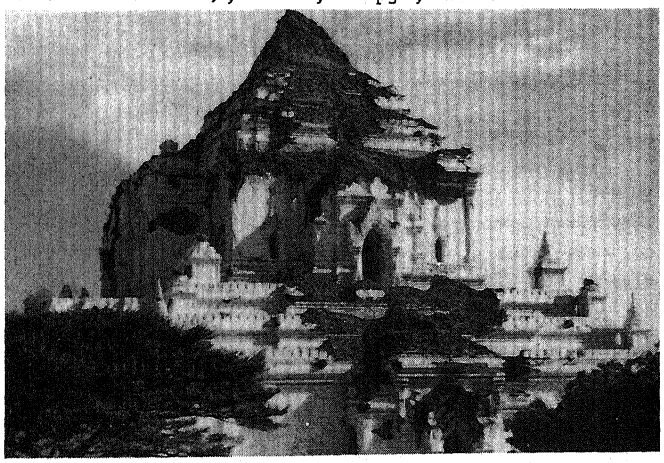

Fig. 1. Gawdawpalin Temple – damages due to the earthquake

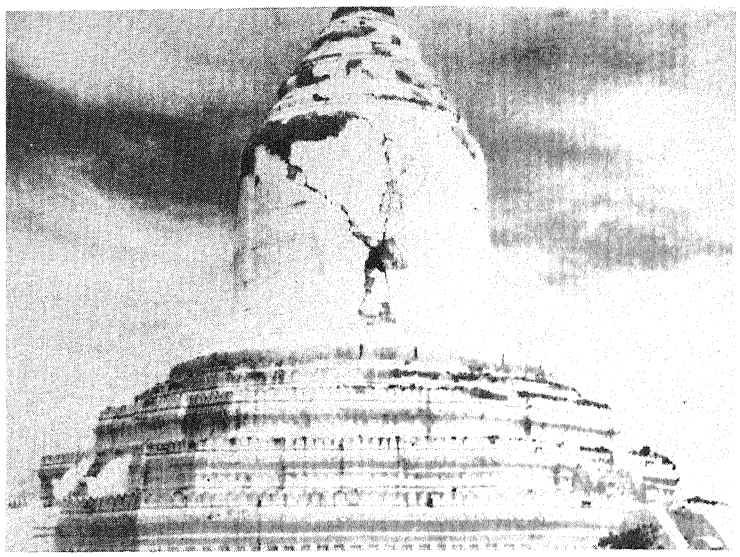

Fig. 2. Lokananda Pagoda — damages due to the earthquake

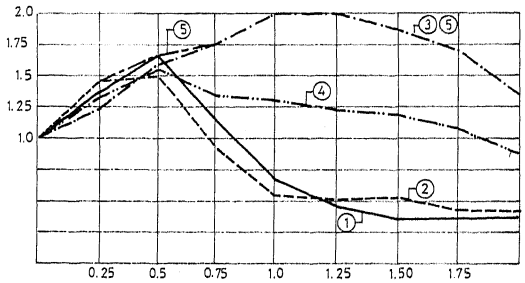

Fig. 3. Normalized response spectrum for damping c = 10 % Ccr

1. El Centro, Comp. N–S
2. Monte Negro Earthquake, Ulcinj 1, Comp. N–S
3. Bucharest record, Comp. N–S
4. Average spectra values
5. Envelope

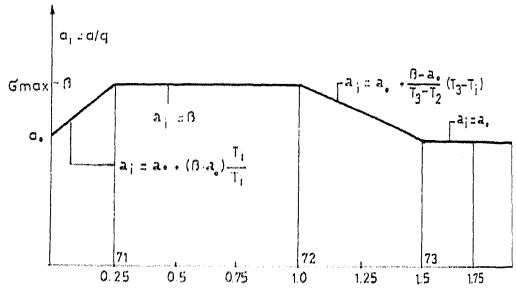

Fig. 4. Design response spectra

a_0 = Value of peak ground acceleration

β = Maximum spectral ordinate

β_{max} = 1.4

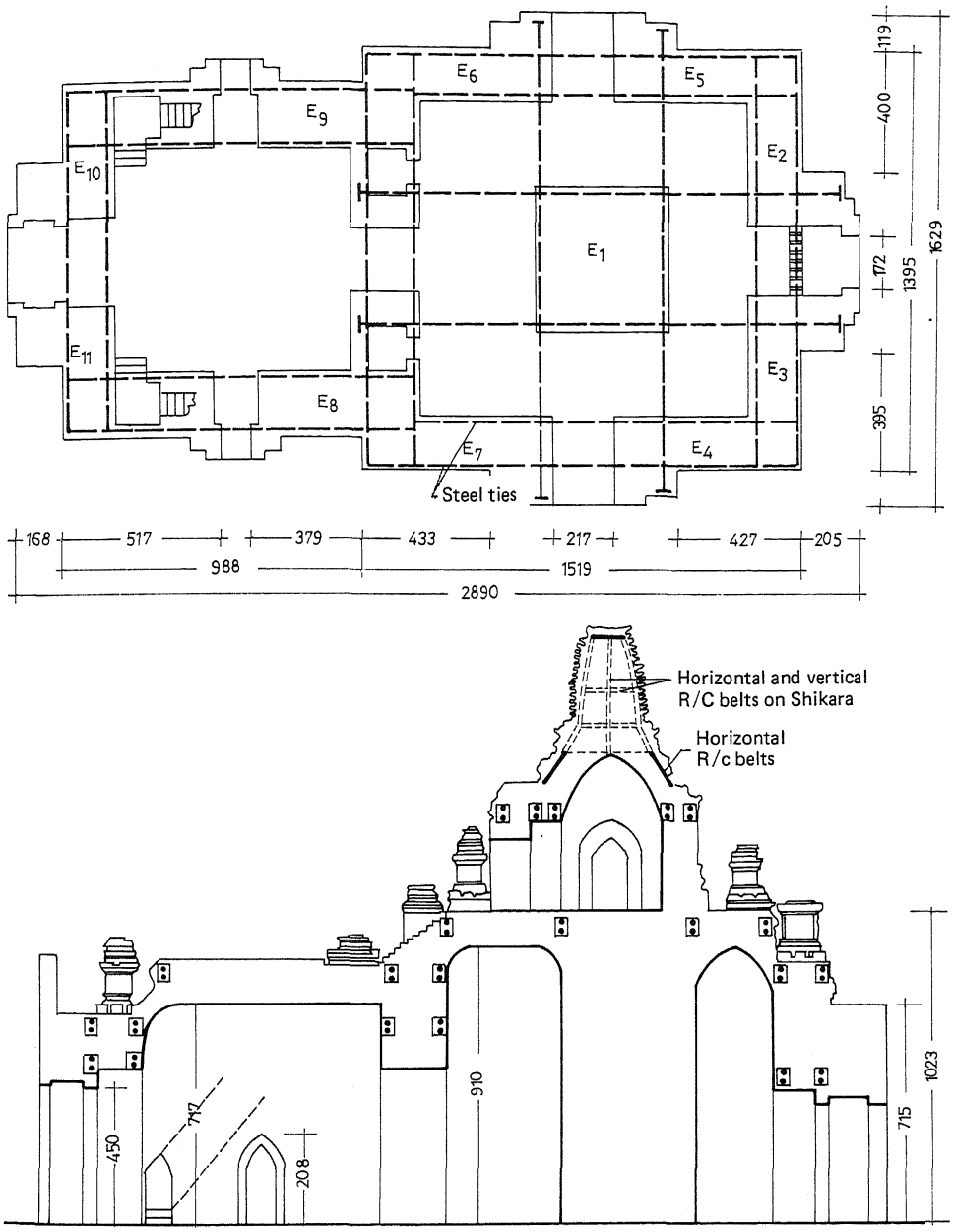

Fig. 7. Strengthening and repair of small and medium size temples by South Guni Temple, plan of first floor and cross section

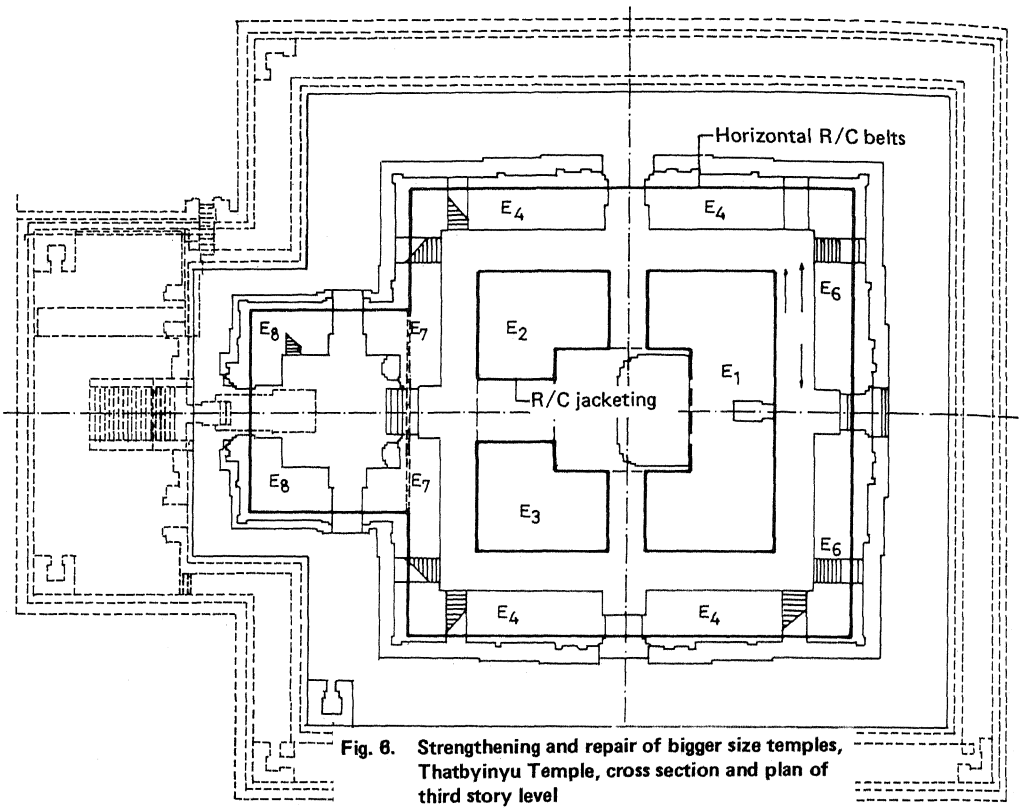

Fig. 6. Strengthening and repair of bigger size temples, Thatbyinyu Temple, cross section and plan of third story level

NAME OF MONUMENT	E-W direction frequency(Hz)		N-S direction frequency (Hz)	
	exper.	anal	exper.	anal.
Gawdawpalin Temple	2.48	2.53	2.16	2.14
Thatbyinnyu Temple	2.16	2.32	1.92	2.05
Myauktaw Ukin Temple	2.60	-	4.80	-
That Kyamuni Temple	3.60	3.60	3.20	3.16
South Guni Temple	4.40	4.40	3.40	3.86
Htilaminlo Pagoda	2.80	3.0[illegible]	[illegible]	[illegible]
North Guni Temple	3.40	3.36	3.00	2.77
Htilominlo No.1931	3.80	3.88	3.60	3.63
Upali Thein Hall	5.80	11.75	4.60	4.64
Alopyi Temple	4.60	5.17	4.20	4.23
Temple No.1843	6.00	5.90	5.20	5.46
Htanuha Temple	3.60	3.42	3.60	3.39

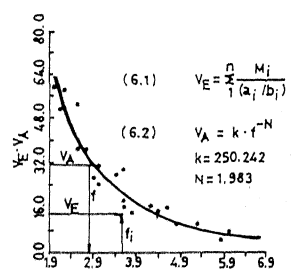

Fig. 5. Correlation of experimental and analytical results

Fig. 6. Relationship between natural frequencies and geometrical proportions of structures