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Innovative Strengthening of Structures for Earthquakes

Renforcement innovateur des structures exposées aux tremblements de terre

Innovative Verstärkung von Bauwerken für Erdbeben

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SUMMARY

The paper describes new innovative methods for the strengthening of the lateral load resisting frame of a structure using the post-tensioning technique. After a brief review of general concepts, selected applications of unreinforced masonry and precast concrete buildings are presented. The paper concludes that post-tensioning is a very effective method for the strengthening of structures since it provides improved strength, improved cracking behaviour and makes optimum use of the existing structure.

RÉSUMÉ

Cet article décrit de nouvelles méthodes de renforcement de structures sollicitées par des charges horizontales en utilisant la technique de la précontrainte. Après un bref aperçu du concept général, l'article donne quelques applications dans le domaine de la maçonnerie non armée et dans celui de bâtiments en béton préfabriqué. Il y a démontré que la précontrainte est un moyen efficace de renforcement de structures qui permet d'augmenter la capacité portante des éléments porteurs et, en outre, d'obtenir un meilleur comportement à la fissuration et une utilisation optimale de la structure existante.

ZUSAMMENFASSUNG

Der Artikel beschreibt neue Methoden zur Verstärkung der Tragstruktur von Bauwerken für Horizontallasten mit Hilfe von Vorspannung. Nach einem kurzen Ueberblick über das generelle Konzept der Verstärkungsmethode werden ausgewählte Anwendungen an unbewehrten Mauerwerks- und vorgefertigten Betongebäuden illustriert. Es wird gezeigt, dass Vorspannung ein sehr effizientes Verfahren zur Verstärkung von Tragstrukturen ist, da sie neben erhöhter Tragfähigkeit ein verbessertes Risseverhalten bewirkt und optimalen Gebrauch der bestehenden Tragstruktur macht.



1. INTRODUCTION

Earthquakes still belong to the most devastating types of disaster. They can cause a large number of fatalities and huge economical losses. Often, areas with old, unreinforced masonry structures will suffer major damage, [1, 2]. However, reinforced concrete buildings and engineering structures such as bridges may also be severely hit as demonstrated in the 1989 Loma Prieta Earthquake in California. While the design and detailing of new structures seems to provide an adequate level of safety for seismic loads, in general, this may not be true for older structures. A major percentage of buildings has even been built in a pre-code period, probably without consideration to lateral loads. To prevent excessive loss of life such structures need to be strengthened to provide a minimum acceptable level of safety. By definition, such minimum requirements will not provide the same level of protection as codes for new structures, in general, see e.g. [3].

This paper illustrates the potential for strengthening of structures using the post-tensioning technique. It focuses on the strengthening of the lateral load resisting frame of a structure for inadequate shear and flexural strength and/or ductility. After a brief review of general concepts, selected applications of unreinforced masonry and concrete structures will be presented. Although important, upgrading of connections between structural elements, such as anchoring walls to diaphragms, will not be considered in this paper.

Typical approaches for the strengthening of the lateral load resisting frame of a structure include the addition of structural steel frames and the application of reinforced shotcrete to existing walls, respectively. While both approaches improve the strength of a structure they usually require major changes to the structure such as the provision of new foundations for the steel frame or added mass of the shotcrete, have a major visual impact on the appearance of the structure, or reduce the usable space in the structure. The proposed strengthening techniques with post-tensioning avoid these disadvantages. They make maximum use of the existing structural materials masonry or concrete and therefore, do not require new foundations, in general. Placing the post-tensioning tendons inside existing members minimizes the impact on the appearance and use of the structure.

2. GENERAL CONCEPTS

The basic concept of the proposed method is to improve the strength and/or ductility of the vertical members of the lateral load resisting frame by introducing prestressed reinforcement along the vertical members. The prestressed reinforcement is designed to take all the tension forces associated with the expected lateral loads and/or displacements while compression forces are assigned to the existing masonry or concrete.

Particularly in older constructions, vertical members of the frame have been designed to carry mainly axial loads but only little flexure and shear due to lateral loads. This typically led to the use of unreinforced masonry or lightly reinforced concrete. For such unreinforced or under-reinforced members, the tensile strength of the material influences the behaviour considerably. Such members tend to show a low strength for lateral loads and, perhaps even worse, a brittle behaviour once the tensile strength is exceeded. Provision of a reinforcement

exceeding minimum requirements, i.e. to produce a strength exceeding cracking load of the member, will considerably enhance the behaviour of the member both regarding strength and ductility. The different types of behaviour are illustrated in Fig. 1. Curves (1) and (2) in Fig. 1 show the behaviour of unreinforced and underreinforced members, respectively, while Curve (3) illustrates the improved behaviour of a member strengthened according to the proposed technique. It may be worth nothing that the favourable behaviour according to Curve (3), in Fig. 1 may be achieved by either bonded non-prestressed and prestressed reinforcement or unbonded prestressed reinforcement, and for both shear and flexural members, see [4].

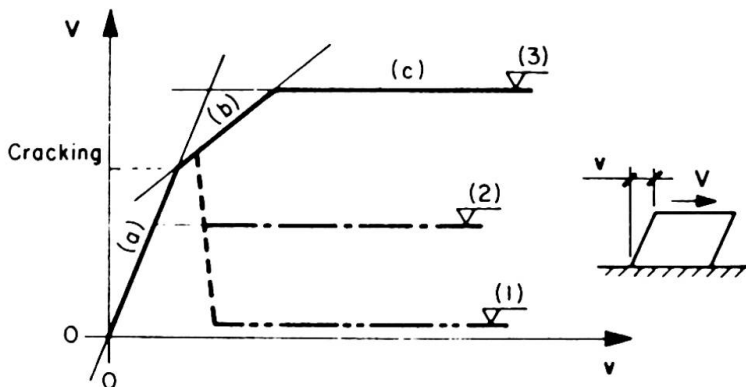


Fig. 1:
Adequat prestress improves strength and ductility of members.

To achieve a reasonable ductility of a member even without special confinement reinforcement the level of axial prestress and/or the yield force of the reinforcement shall be kept low, say below 25 % of the axial compressive strength of the member, [5]. This will provide displacement capacities of several times the nominal yield displacement of a member under cyclic load reversals.

3. SELECTED APPLICATIONS

The following will give a short description of two examples in which post-tensioning has been used to strengthen structures or members. These examples are taken from work proposed and carried out by VSL Corporation, Campbell, CA, after the 1989 Loma Prieta Earthquake.

3.1 Unreinforced masonry, 2-storey building

The building, locally known as Brick Castle, is approximately 100 years old, Fig. 2. It consists of unreinforced clay brick masonry exterior walls, 200 mm thick, timber floors, partitions and roof, and a stone rubble foundation. The plan of the building is fairly irregular with lots of window and door openings and a particularly small total wall length on the South side, Fig. 3. During the Loma Prieta Earthquake the building had lost parts of masonry parapets, suffered considerably structural and non-structural cracking and as a consequence was red-tagged, i.e. habitants were no longer allowed to use the building. Structural cracking consisted mainly of diagonal shear cracks on the South side of the building, and vertical cracks along window and door openings.

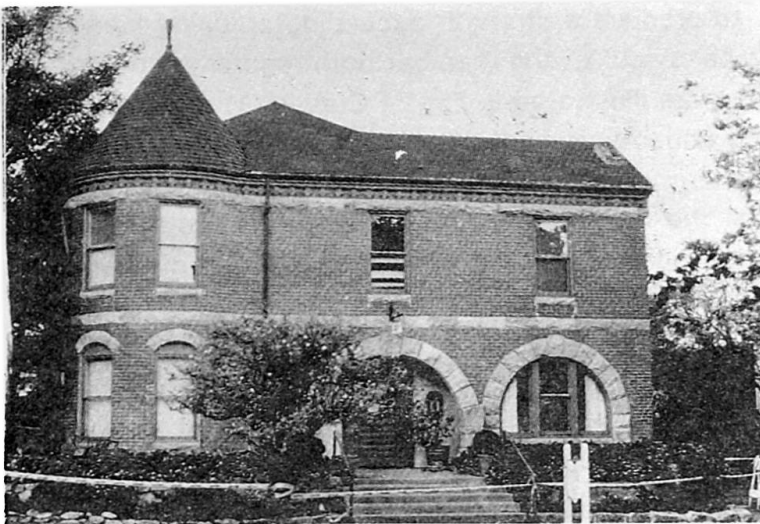


Fig. 2:
Brick Castle, Los Gatos, CA.

Structural repair work included grouting of cracks in the masonry walls, reconstruction of damaged parapets and the addition of continuous structural steel chords and anchors along the floor-wall connections to properly tie the walls to the floor diaphragms.

Preliminary in-situ testing indicated that the masonry was strong enough to allow the use of post-tensioning to increase the shear strength of the building. Consequently, vertical tendons were introduced in load-bearing walls, see Fig. 3, anchored in the stone rubble foundation and a continuous reinforced concrete beam, subsequently added at roof level. Tendons were placed in small slots at wall corners, thus tendon eccentricities were minimized and taken by cross walls. For long-term corrosion protection, monostrand tendons were used, i.e. individually greased and plastic sheathed strands. For fire protection and added mechanical protection, the slots with the monostrand tendons were grouted.

Repair and strengthening work started in fall 1990 and was completed first half 1991. Placing and stressing of monostrand tendons did not reveal any problems.

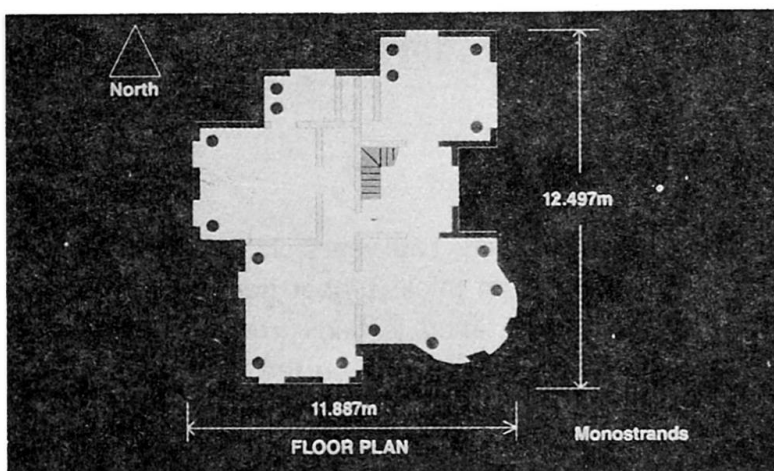


Fig. 3:
Floor plan of Brick Castle with tendon location.

3.2 Precast concrete, 7-storey building

This example considers an approximately 30 years old apartment building. It consists of a precast concrete one-way floor system supported by precast concrete wall panels, 140 mm thick, and an in-situ reinforced concrete mat foundation. In plan the building is of L-shape, each section having a substantial number of fairly regularly arranged shear walls. During the Loma Prieta Earthquake, walls panels in the ground and 2nd floor experienced severe cracking along the vertical edges. Removal of the concrete in these areas in selected wall panels, revealed two large bars, diameter 36 mm, along the panel edges without stirrup confinement. These bars were spliced at floor levels to adjacent panel reinforcement through eccentrically welded steel plates. Many of these connections had failed during the earthquake.

Since, for obvious detailing reasons, it was not possible to develop the strength of the provided main reinforcement, it was decided to remove it completely and to replace it with vertical post-tensioning. Post-tensioning tendons consisted of seven 0.5 in. strands, placed inside a thick-walled structural steel pipe. While the dead end of the tendons was in the foundation, the stressing end was at the fourth floor, in general. The steel pipe was anchored into the concrete wall panels and floors with dowel bars, diameter 16 mm, and bearing plates welded to the pipe at all floor levels, respectively, Fig. 4. After installation of pipe and strand, the wall edges were poured back with a pea gravel concrete, to their original dimensions. To minimize spalling of concrete cover in the future, a light reinforcing mesh and a special confinement reinforcement were placed along the pipe. After stressing of the tendons, the pipe was grouted to allow composite action of the prestressing and structural steel.

Strengthening of this apartment building was done in 1990. Stressing of the multistrand tendons in the relatively thin wall panels did not reveal any problems even in cases where panels were stressed eccentrically, at one end only.

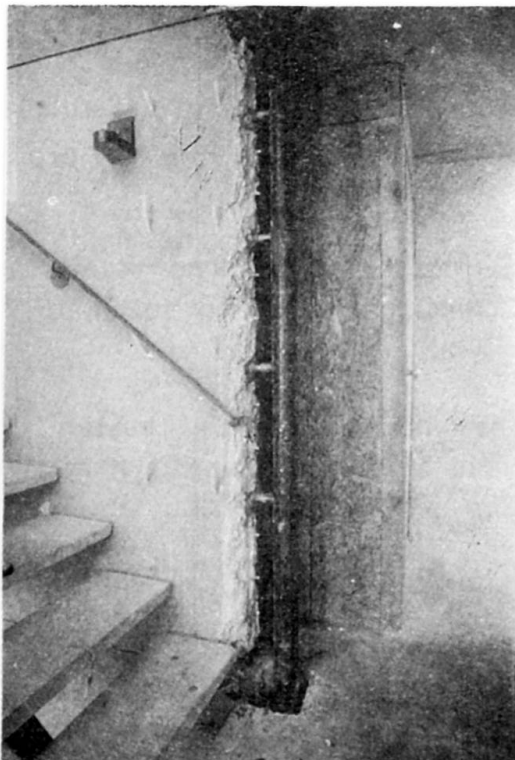


Fig. 4:
Post-tensioning tendon placed in structural steel pipe along panel edge.



4. CONCLUSIONS

Strengthening of structures with post-tensioning tendons is most effective since it provides improved strength through a continuous reinforcement from anchorage to anchorage avoiding potential weakness at multiple laps of reinforcing bars. Further, the provided prestress improves the cracking behaviour of a structure and therefore, helps to reduce damage under low to moderate seismic loads.

The proposed strengthening technique makes optimum use of existing materials. Thus, major structural alterations such as the introduction of structural steel frames or the addition of new foundation can be avoided, in general.

While basically many types of structures can be strengthened with the proposed technique, it is best suited for larger structures made of reasonably strong masonry or concrete. Two selected examples have been described in this paper. Other examples such as the strengthening of an unreinforced masonry church and reinforced concrete columns are presently under consideration.

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