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Earthquake Resistance of Masonry Structures Strengthened with CFRP-Sheets

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Summary

Two 60 year old, adjacent residential buildings in the city of Zurich, Switzerland, are converted into an office building. Major changes to the structural system were necessary; in particular, some load bearing walls had to be replaced or reinforced to resist potential earthquake forces. The reinforcement is carried out by carbon fiber reinforced plastic sheets (CFRP), which are glued to the existing shear wall and anchored in the RC-slabs. The efficiency of this system was confirmed by the Swiss Federal Laboratories for Materials Testing and Research EMPA.

1. Introduction

In recent years, engineers are more often faced with the reconstruction or upgrading of existing buildings rather than designing new ones. Although it would be more economical in some cases to replace a building completely, city planning regulations and historical reasons do not allow to do major changes to many buildings, especially on facades. As most of the older buildings are not designed to resists earthquake forces, architects and engineers are challenged to find economical solutions to make structural systems and the structural elements earthquake-resistant. Especially when the usage of a building is changed from living to office space and shopping areas, major changes of the structural system are required. Consequently, old structural elements are replaced by new ones, or they have to be strengthened. In many cases it is desirable to maintain as many old structural elements as possible if they can be strengthened economically, i.e. without undue interference with other remaining structures or the usage of space.

In the city of Zurich, two adjacent 60 year old residential buildings of 6 storeys are converted into one office building. Major structural changes are necessary. Old wooden slabs are replaced by RC-slabs. Load bearing masonry walls are partly eliminated and replaced by new ones. Some of the remaining load bearing masonry walls are strengthened by using carbon fiber sheets, so that the earthquake load can be resisted. The carbon fiber sheets are glued to the masonry wall and anchored in the slab. This strengthening method has been tested in full scale tests at the Swiss Federal Laboratories for Materials Testing and Research EMPA. These tests showed a significant increase in strength and ductility of the CFRP-strengthened masonry wall elements [Schwegler G. 1994a]. As it is easy to apply and economical, this strengthening method is very promising.

In the following, the application of the above mentioned method of strengthening masonry walls by CFRP-sheets is demonstrated [Ernst Basler & Partners Ltd., 1995].

2. Reconstruction Project

Two adjacent residential buildings are functionally joined so that they can be used as offices (Figure 1). All structural elements are affected by this conversion. Only a small number of them remains more or less untouched. All inner walls are removed. The outer wall on the rear side of the building is replaced by a light weight construction. The facade looking onto the main street (called Mühlebachstrasse) has to be retained. However, in the center part a large window is created (Figure 2). On the ground floor level, the load bearing walls are replaced by a new arrangement of columns to create shop windows (Figure 3). The fire protection walls separating the neighbouring buildings remain.

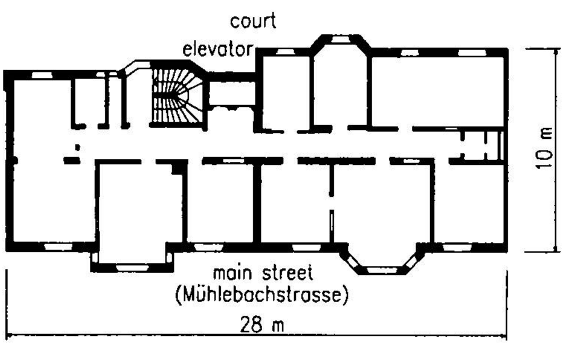

Figure 1: Existing bearing structure on 2nd floor before remodeling

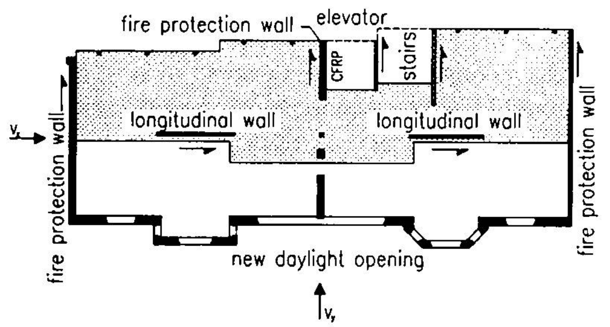

Figure 2: Bearing structure 1st to 4th floors, after remodeling

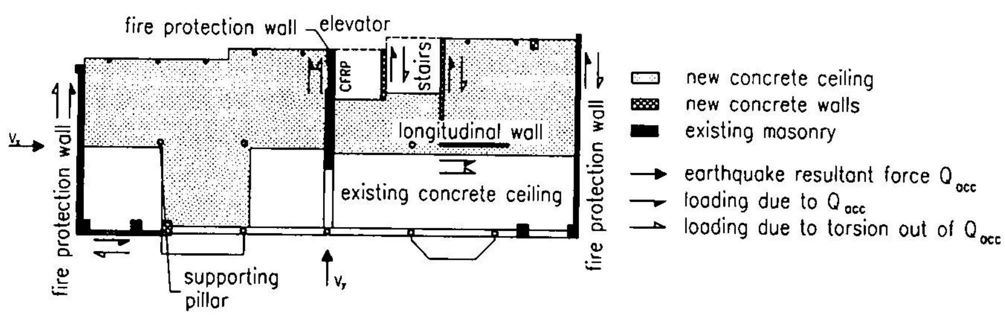

Figure 3: Bearing structure ground floor, after remodeling

These major changes to the structural system lead to a markedly different dynamic behavior than before. Both the stiffness and the strength have thus been altered, which had to be considered in the design against earthquakes.

3. Earthquake Resistance

The major horizontal earthquake forces act at the floor levels. The floor slabs have to be stiff and strong enough to transfer these forces into the shear walls, from where they are carried to the foundation. In the transverse direction of the building, the lateral resistance is provided by the shear walls of the stair case, the fire protection walls of the elevator shaft and by the double masonry wall to the adjacent buildings. In this direction, the stiffness, mass and strength are more or less symmetrically arranged (Figure 2).

In the longitudinal direction there are two load resisting walls in the center of the building from the 1st to the 4th floor. On the ground floor level, one of these two walls is replaced by an eccentric wall in the facade. Should it come to an earthquake, this leads to significant torsion in the longitudinal direction. To balance this torsion, the structural elements in the transverse direction need to be taken into account.

The existing wooden floor slabs are not rigid and not strong enough for the lateral load transfer and have thus to be partly replaced by RC-slabs. The large lateral forces on the shear walls of the elevator shaft required a strengthening which was done using carbon fiber sheets.

4. Characteristics of the CFRP Strengthening Material

The CFRP-sheets are a combination of unidirectional high strength carbonfibers and of an epoxy resin matrix. This leads to a material of high strength and stiffness. CFRP-sheets are produced in strands of unlimited length by the pultrusion-process and delivered to the site of application in rolls.

CFRP-sheets have major advantages over sheets made of steel. CFRP-sheets are superior with respect to corrosion, fatigue behavior and strength. In addition, they are light and easy to handle and simple in the application.

The most relevant material characteristics of the CFRP-sheets are shown in table 1.

Type of strengthening material	Ultimate tensile strength $\sigma_{u\parallel}$ [N/mm^2]	Young's Modulus $E_{\parallel}$ [N/mm^2]	Ultimate tensile strain $\varepsilon_{u\parallel}$ [%]
C-Fiber T700S	2400	155'000	1.90
steel	235	210'000	> 5%

Table 1: Major material properties of CFRP-sheets as compared to steel-plates

Compared to steel, CFRP shows linear elastic material properties, and the ultimate tensile strain of the applied CFRP-sheets amounts to $\varepsilon_u = 1.9\%$. These material properties have to be taken into account during the planning process. The large scale tests conducted at EMPA show that with an appropriate distribution of the CFRP-sheets on the masonry wall, considerable system's ductility can be achieved [Schwegler G., 1994a, 1994b].

5. Application of the CFRP-Sheets

Before gluing the CFRP-sheets to the masonry walls, the substrate has to be freed of all lose or unsound particles, such as rendering and plaster materials, or paints and wallpapers, etc. In order to obtain a perfect straightness in the final position, all protruding surface points have to be chipped off and all survace depressions leveled out with epoxy adhesive. After applying the special epoxy adhesive to both contact surfaces, the CFRP-sheets are then fixed to the masonry wall with light hand pressure, and full contact is ensured by further pressure application with simple rubber rollers (Figure 4).

The CFRP-sheets are anchored in the adjacent RC-slabs and -walls. Thus stress concentrations in the masonry walls are thereby avoided. For each anchorage, a cavity is worked into the concrete, or core drillings are carried out. Next, the ends of the sheets are equipped with an adhesive bridge and fed into the cavities or drilling holes, before filling the holes with liquid epoxy-mortar. Thanks to this new anchorage technique, only a very short length is needed to anchor the forces in the concrete (Figure 5).

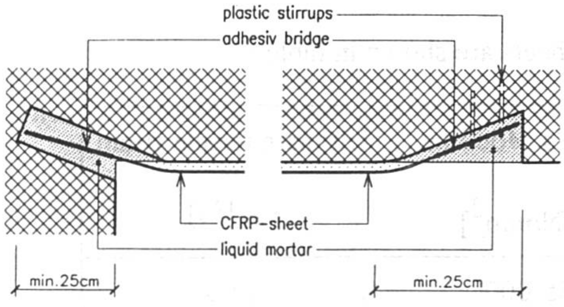

Figure 5: Anchorage of the CFRP-sheets in the concrete

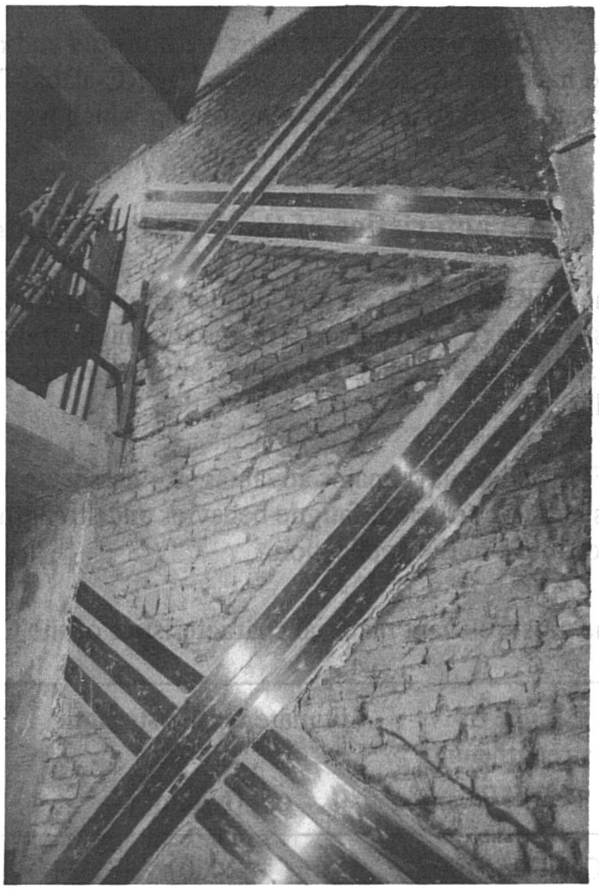

Figure 4: Distribution of CFRP-sheets on masonry shear wall

In order to limit the amount of work, the CFRP-sheets are only used on one side of the load-bearing wall. The tests at EMPA have shown that the resulting eccentricity only causes negligible effects on the strength of the shear wall.

6 Dimensioning of Reinforced Shear Walls

For dimensioning a CFRP-reinforced shearwall, the method of "stress-fields" can be used [Muttoni A., Schwartz J., Thürlimann B., 1988]. This method allows to estimate the shear wall resistance easily and with sufficient accuracy. The flow of the forces in the shear wall can be described by using truss models. The forces of each strut of the truss model correspond to the resulting inner forces.These resultants are then converted into static equivalent stress-fields. In figure 6, the course of the stress-field inside the CFRP-reinforced masonry walls is pictured. To keep the illustration simple, only one symmetrical half of the stress-fields is shown.

The horizontal forces that are acting at the floor levels together with the vertical forces in the load bearing walls lead to diagonal stress-fields which carry the compressive forces. The tensile forces are carried by the CFRP-sheets. The stresses of a stress-field are uniaxial on their whole length. In the areas of application of forces, referred to as knots, the state of stresses is biaxial. All other areas are free from stresses.

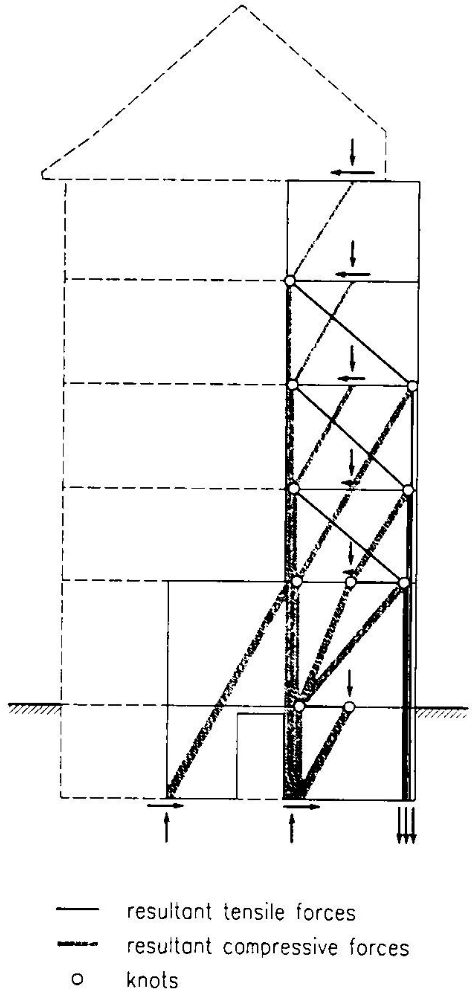

Figure 6: Stress-field of the CFRP-reinforced load bearing masonry wall

The angle between the CFRP-sheets and the vertical line should be chosen as large as possible to increase the lateral resistance. The dimensioning of reinforced load bearing masonry walls using the method of stress-fields is described more detailed in [Muttoni A., Schwartz J., Thürlimann B., 1988] and [Schwegler G., 1994a].

7 Conclusions

The application of CFRP-sheets to the existing load bearing masonry shear wall significantly increased its lateral resistance and ductility. Alternative methods such as reinforced shotcrete or the replacement of the wall would have been more expensive. Besides, strengthening by reinforced shotcrete would have lead to an additional thickness of 700 mm, which for architectural reasons would not have been acceptable.

The CFRP reinforcing method for masonry walls proves to be a very efficient method in the field of earthquake resistance design, as it is economical and easy to apply.

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