SEISMIC RETROFIT WITH PRE-TENSIONED PIN-LOADED CFRP TENDONS

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Introduction

Earthquake forces occurring in structures must be transferred through the structure into the foundations. Highly endangered are especially masonry structures, since the tensile and shear strengths of not strengthened masonry do not meet current standards. Most masonry structures worldwide must be post-strengthened. The goal of the present work was to develop novel methods for strengthening those load bearing elements which are most highly subjected to earthquake forces in multi-storey buildings. These are the shear walls in the lowest storey. The strengthening should increase the system ductility, generate uniform crack distribution over the entire surface of the shear wall and increase the load carrying capacity. Two methods of strengthening were developed at EMPA in the early 1990ties: i) CFRP strips were bonded diagonally to masonry walls and anchored in the adjoining ceiling and floor slabs, and ii) the walls were strengthened with conventional sheets of woven fabrics. Both methods were successful however have the disadvantage that they disturb the appearance of masonry walls. Therefore a new technique for post-tensioning of masonry walls with CFRP tendons has been developed.

Pin-loaded CFRP strap elements

A carbon fiber reinforced laminated pin-loaded strap, as shown in Figure 1a, might provide a practical tension element for the shear enhancement of masonry walls. Such an element can consist of a unidirectional FRP, having a fiber volume fraction of about 60%, wound around two cylindrical pins in a racetrack shape. The two pins transfer tensile load between the structure, and the fully consolidated strap. Laboratory experiments and analytical modeling has shown that there are severe stress concentrations in the region where the strap and the pin meet. The tensile resistance of the strap is therefore limited to 40 to 60% of the material's expected unidirectional strength. This is attributed to stress concentrations, which lead to premature failure. An alternative option to reduce the undesirable stress concentrations and to reduce cost is the use of a non-laminated strap. The concept is shown in Figure 1b. The CFRP strap now comprises a number of unidirectionally reinforced layers, formed from a single, continuous, thermoplastic tape of 0.12 mm thickness. The tape is wound around the two pins and only the end of the outermost layer is fusion bonded to the next outermost layer to form a closed loop. The non-laminated strap element enables the individual layers to move relative to each other which allows an equalization of forces in the layers as the strap is tensioned. The stress concentrations are reduced since the new structural form is more compliant than the laminated equivalent. Control of the initial tensioning process reduces interlaminar shear stresses so that a more uniform strain distribution in all layers can be achieved. The approach allows greater flexibility in terms of the geometry of the tendon, and it can be manufactured on site. Moreover, the concept is going to be less expensive because there is no consolidation process required.

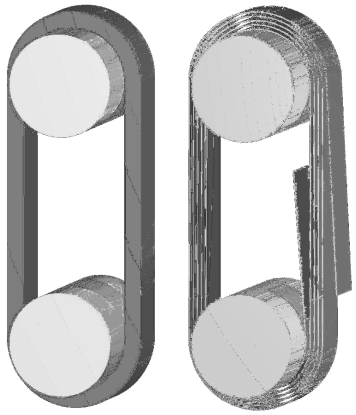

Fig.1: Conceptual design of pin-loaded strap elements

Reliability aspects

The Weibull modulus "m" is an important parameter for characterizing the strength distribution of brittle solids. A low value of m (e.g.<10) implies considerable uncertainty about the strength of a specimen. In practice, many ceramic materials exhibit Weibull moduli in the range 2 to 15. Sommer et al. [1] reported values of m = 5.25 for strength properties of single carbon fiber filaments.

Fifty-three straps were produced from 12 mm wide carbon fiber tape with Nylon matrix (Toray T700 / PA 12). Various configurations in terms of number of layers, N, length, L, and pin diameter, D, were investigated. The tensile tests for the smaller pin diameters, summarized in Table 1, were performed on an Instron 1251 testing machine. The larger pin diameter straps were tested on an Instron 1346. The pin diameter had to be increased for the straps consisting of forty or more layers to prevent failure of the steel pin due to extensive bending and shear stresses.

Table 1: Summary of experimental investigation on non-laminated pin-loaded straps.

Number of layers, *N*	1	10	20	30	40	40	40	50	60	70
Specimens tested, *n*	6	6	6	6	7	6	3	7	4	2
Pin diameter, *D*	30	30	30	30	50	50	50	50	50	50
Length, *L*	700	700	700	700	700	350	1500	700	700	700
F_{ult} [kN]	6.2	50.0	101.2	157.8	207.4	173.8	204.0	249.0	269.8	278.0
s [kN]	0.3	1.2	2.8	3.4	3.8	12.0	3.6	4.9	10.2	14.1
C. O. V [%]	5.5	2.5	2.8	2.1	1.8	6.9	1.8	2.0	3.8	5.1
Weibull modulus, *m*	16.0	33.6	32.0	40.9	49.2	12.5	43.7	47.2	21.6	13.8

Load carrying capacities, F_{ult} , are given instead of stresses because of variations in the tape dimensions, hence inaccurate measurements of the cross-sectional area. The highest mean strength was attained with a single layer containing a fusion bonded joint. Failure occurred in the joint, which may be the reason for the large variability. Only minor differences in the capacity per tape were observed for straps consisting of ten up to fifty layers. Furthermore, the variability of these sets was considerably reduced. Specimens consisting of less than thirty layers failed in a brittle manner, whereas those with thirty or more layers started to fail with localized fractures in the pin region starting with the innermost layer. Substantial, clearly visible, damage was accumulated in the pin region before the final failure occurred. This experimental observation is also reflected by the increase of the Weibull moduli "m" given in Table 1. A considerable reduction of the capacity per tape was observed in specimens consisting of sixty and more layers. It suggests that failure of such straps is dominated by excessive through-thickness stress components. Similarly, the short specimens (L = 350) exhibited a considerable reduction of the load carrying capacity. This is attributed to an uneven strain distribution between individual layers because a reduced length requires increased relative displacement to attain an even strain distribution. The large variability in the set N40L350 indicates a difference in the tape qualities since the specimens are made from different production batches. Ongoing outdoor creep tests are being carried out on two specimens consisting of twenty-seven layers. They are loaded to 90 % of the average static load carrying capacity of equivalent straps. The specimens are being tested since eight years under these severe loading conditions without failure. The dramatic increase of the Weibull moduli presented in Table 1 compared to the values mentioned above for single fibers is attributed to the large number of filaments present in the composite and the ability of the matrix to transfer load into the fibers across the interface, thus resulting in load redistribution effects in the vicinity of cracks. The consequence is a much more reliable material than expected from tensile strength properties of single fibers.

Applications

The above described pin-loaded CFRP tendons are successfully in use since five years as stays of some of the tallest cranes in the world, since three year in bridge construction and since two years as external post-tensioning elements for the seismic retrofit of masonry walls.

For the seismic retrofit of masonry walls there are the following advantages compared to adhesively bonded CFRP strips or woven fabrics: i) much better effectiveness; ii) easy to accomplish quality assurance; iii) very fast installation, which saves labor hours; iv) only very small disturbance of the appearance of a masonry wall what is especially important for heritage structures.

Conclusions

The pin-loaded CFRP tendons developed at EMPA proved to be very reliable and lightweight, are not corroding, not suffering stress relaxation and show an excellent fatigue behavior. They are beside applications in mechanical engineering especially well suited for rehabilitation of civil structures particularly for the seismic retrofit of masonry walls. This will further on increase the already high demand for carbon fibers in applications of civil structures

References

1. Sommer U., Kainer K. U., Böhm E. and Krüger G., Charakterisierung von Hochleistungsfasern für die Verstärkung von Metallmatrix-Verbundwerkstoffen, in Ziegler G. (Ed), Verbundwerkstoffe und Werkstoffverbunde, DGM Informationsgesellschaft 1996, pp. 375-378.