Fixing Steel Braced Frames to Concrete Structures for Earthquake Strengthening

Gilbert Balbuena

Hilti New Zealand Ltd, New Zealand.

Jakob Kunz

Hilti Corporation, Schaan, Liechtenstein.

2009 NZSEE Conference

ABSTRACT: Steel braced frames are widely used to upgrade concrete structures for earthquake loads. They are used both to strengthen the structure and to increase its ductility. In order to transfer the horizontal shear loads from the concrete structure to the steel braced frame, a reliable connection between the two is essential. It must be able to transfer the full capacity of the steel frame with only limited displacements. The behavior of two different fixing methods has been investigated in research programs in Japan and in Europe. A device to ensure an evenly distributed load transfer to a long row of anchors has been developed to meet the requirements of such applications.

1 INDIRECT CONNECTION: LOAD TRANSFER THROUGH MORTAR JOINT

1.1 Method

The first method investigated is to transfer the earthquake loads from the concrete to the steel frame through a mortar joint. In this case the steel frame is equipped with headed studs at its circumference and post-installed anchors with headed ends are fixed to the concrete structure. When the steel frame has been placed, a spiral reinforcement is put into the space between frame and concrete and a non shrink grout is injected into the space between the existing concrete member and the steel frame in order to connect headed s*tuds and post-installed anchors*.

Figure 1 - Frame prepared for indirect

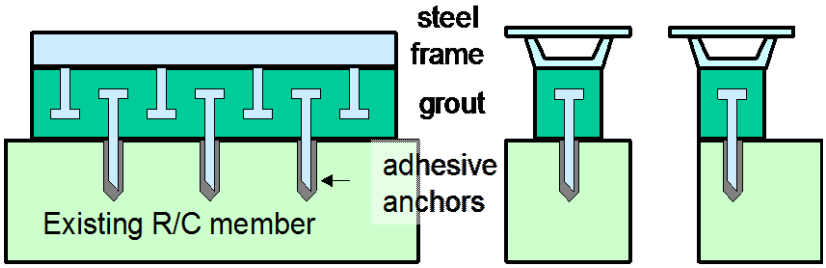

Figure 2 - Indirect connection

1.2 *Test Program*

This type of connection has been investigated in an extensive research program (Yamamoto, 1999). Special attention was given to the fact that the concrete of the structure to be reinforced may be of very low quality. To address this, the first two series of testing consisted of pullout and shear tests of single anchors in normal weight concrete with compressive strengths as low as 5, 10 and 15 MPa and in a lightweight concrete of 15 MPa. The conclusion drawn from the test results is that standard adhesive anchors in low strength concrete can be designed according to standard methods developed for concrete strengths over 20 MPa (Cook, Kunz et al 1998). The results of these tests together with corresponding design recommendations can be found in a paper by Kunz et al. (Kunz, Yamamoto et. al, 2001).

The test series to be presented hereafter assessed the strength, deformation and failure patterns of

indirect connections under cyclic loads. A schematic of an indirection connection is as shown in figure 2. For the tests, twenty specimens were manufactured in sizes and shapes to match that from an actual indirect joint section. Rows of three adhesive anchors were cast into concrete blocks (figure 3). A spiral reinforcement was put between the anchors (figure 4), and on top there was a steel plate with 4 headed studs. Then a mortar joint was injected between concrete specimen and steel plate. Figure 5 shows the loading apparatus. The loading regime included five cycles of increasing displacements as shown in figure 6. In principle, only horizontal shear force was applied to the indirect joint section and the loading beam was confined perpendicularly in order not to apply tensile forces. The constraining force was approximately 0.1MPa. A table of the test parameter is presented in Table 1.

Figure 3: Adhesive anchor with head

Figure 4: group in formwork

Figure 5: Loading apparatus

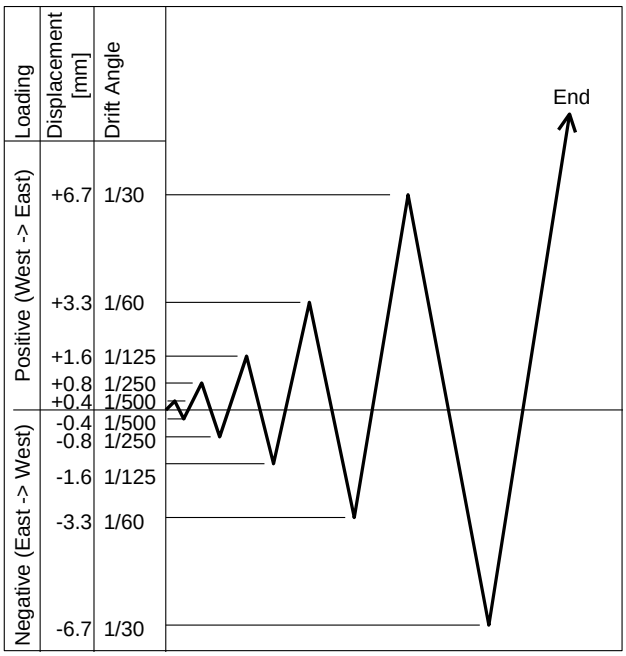

Figure 6: Load cycles

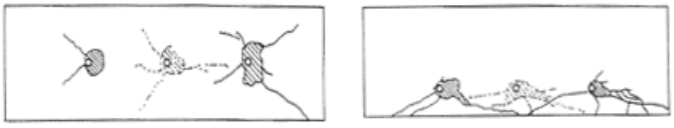

Table 1. Test Parameters for Indirect Joint

Concrete Strength [MPa]	Anchor Diameter [mm]	Edge distances of Anchor Row in Base Plate		Total
		Standard 200/200mm	Eccentric 100/300mm	
5	D19	2	1	3
	D22	1	1	2
10	D19	2	1	3
	D22	1	1	2
15	D19	2	1	3
	D22	1	1	2
LC15 lightweight concrete	D19	2	1	3
	D22	1	1	2
				20 specimens

Horizontal loads and displacement δ of the part filled with mortar were measured. The amount of slip was designed to be divided into relative slip at the interface between mortar and steel frame, δ_{SM}, and relative slip between mortar and base material, δ_{MC}.

1.3 *Test Results*

Figures 7a and 7b show the load-displacement curves and final crack patterns for tests with 19mm diameter bars, standard edge distances and a base block concrete strength of 5MPa for figure 7a and 15MPa for figure 7b. In the first two cycles (drift angles 1/500 and 1/250) the displacement was small, but it became much larger for higher drift angles. Figure 8 shows the resistance components of shear connectors between concrete layers where the interface is roughened [4]. The behavior of the tested specimens is typical for this setup: with small displacements the interlock is sufficient to resist the resulting shear force, with larger displacements the interlock is overcome and the components "pullout-friction" and "dowel bending" take over the load, which results in slip between positive and negative displacements. Figure 7a also shows the typical decrease of resistance when the interlock is overcome and with larger displacements again an increase of resistance due to the increasing importance of dowel bending. The higher the strength of the base material, the less cracks will appear in the matrix and more cracks will appear in the joint. For the eccentric tests, the obtained maximum loads were about identical to those in the standard edge distance tests and the tendencies in cracking were also the same. In the tests with lightweight concrete base material, the shear resistance was about 77% of that obtained in the corresponding tests with normal concrete.

The design of composite steel/concrete sections according to Eurocode 4 takes into account the bearing pressure on the concrete ahead of the connector and the steel shear strength by the formulae given in figure 9. Figure 9 plots the test results against the Eurocode 4 design values for normal strength concrete. It shows that the strength of the indirect joint with post-installed anchors in low strength concrete can be safely designed by the standard formulae developed for composite construction with normal strength concrete.

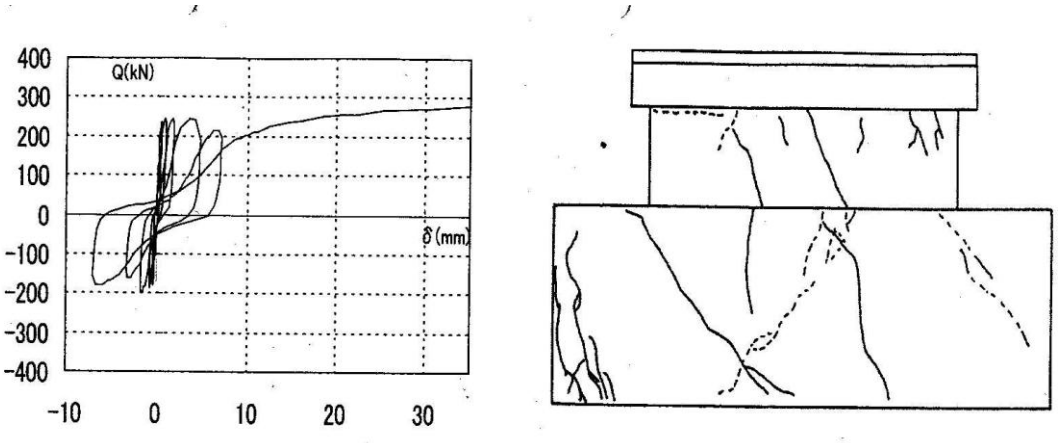

Figure 7a. Cyclic shear test with fc=5MPa

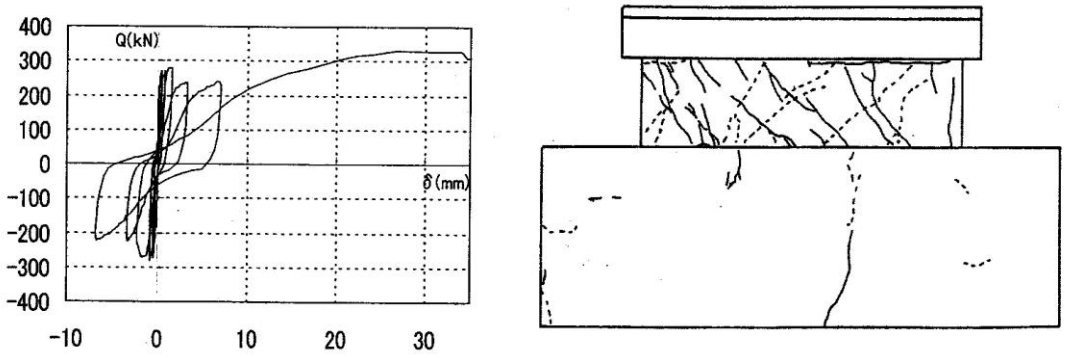

Figure 7b: cyclic shear test with fc=15MPa

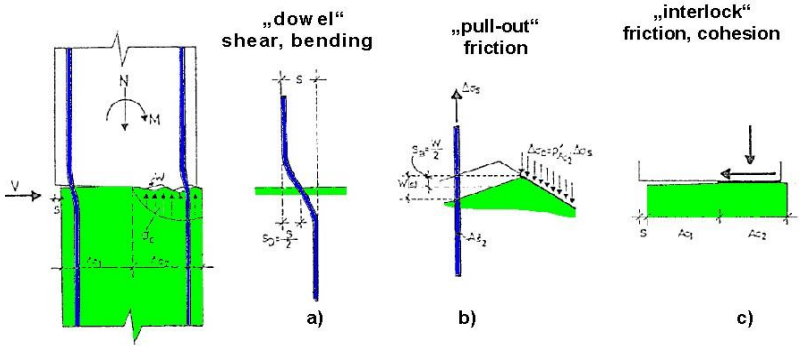

Figure 8: resistance of shear dowels in concrete with rough interface

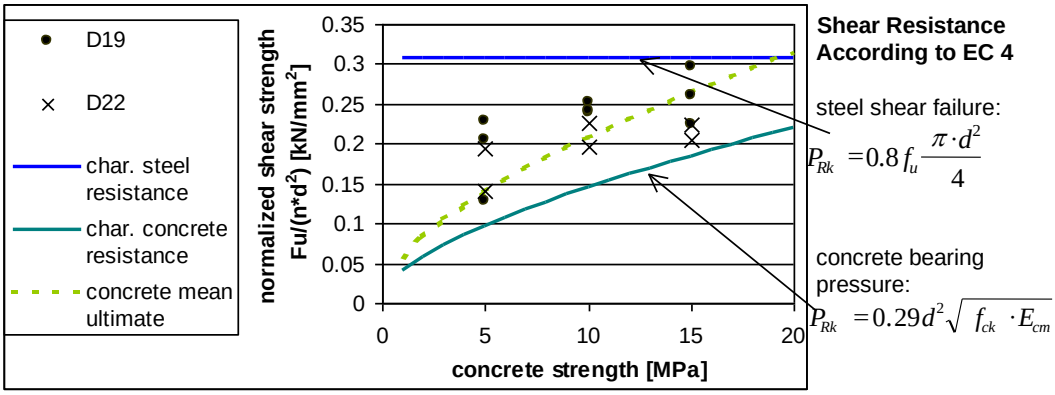

Figure 9: Comparison of normal concrete test results and EC4 design approach

2 DIRECT CONNECTION: FIXING STEEL TO CONCRETE

2.1 *Method*

Another possibility to fix braced steel frames to existing RC frames is the direct connection of the steel parts to the concrete. Adhesive or mechanical anchors usually perform the load transfer from the steel parts to the concrete frame. In the full scale test presented in the following section, the “Ductile Steel Eccentrically - Braced System” (DSEBS) [Bouwkamp, Gomez, Pinto et. al, 2001] of the Darmstadt University of Technology, in Germany, was fixed to a test frame designed by the National Laboratory for Civil Engineering, LNEC, Lisbon, Portugal, with an overall length of 12.50m and a height of 10.80m. The retrofitting procedure involved the introduction of a steel, one bay, ductile eccentrically braced frame with a vertical shear link as shown in figure 10. The overall aim of the full size test was to replace the infilled brick masonry of a single bay by the steel braced frame. According to figure 11, the goal was to increase the ductility of the system while maintaining its actual strength.

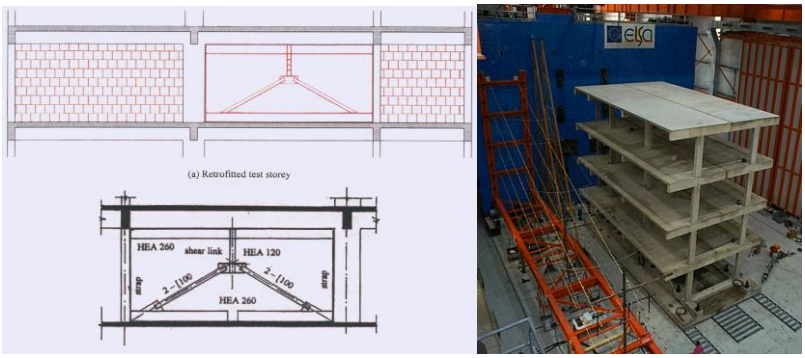

Figure 10: Test Setup

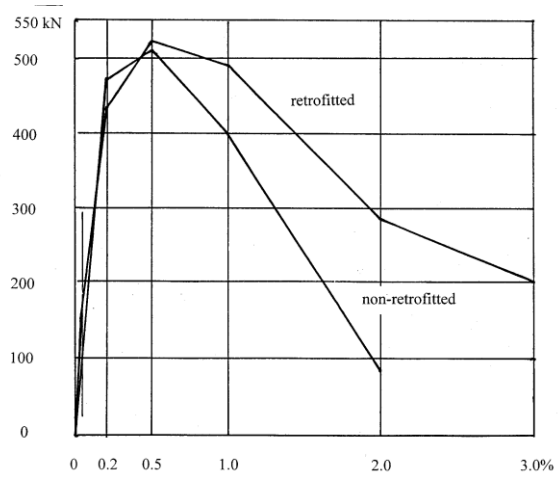

Figure 11: Design

2.2 *Fixing of Frame for Full Scale Test*

The steel frame with the shear link was built into four storey concrete frame building with brick walls into one bay where the bricks were removed. The load was applied to the building floors from the Reaction Wall of the ELSA Laboratories, Joint Research Center, Ispra, Italy. The design of the steel frame aimed at increasing the ductility of the building while maintaining the ultimate load at the initial level. As shown in Figure 11 the ultimate load should be reached at a storey drift angle of 0.5% for both original and strengthened structure. However, the residual load capacity at 2% storey drift angle should be increased by a factor of about 3. The enhanced ductility of the retrofitted structure can be attributed to the actions of the steel frame, in fact specifically the shear link.

The fastening elements were designed to resist shear loads of at least the maximum capacity of the shear link. Therefore, the strength of the shear link (HEA 120) and the geometry of the braced frame governed the design of the anchors. For the Ispra test, the frame was designed for 260 kN of shear loads from the upper beam. The required resistance of each single anchor then depends on diameter, spacing, edge distance of the anchor, and also the load direction and anchor material. Hilti HVZ anchors were used as the anchors for the test. Hilti HVZ are adhesive systems, this means the anchor must snug fit the drill hole. Moreover, the cone designs along the shaft of the HVZ, makes it suitable for application in cracked concrete which is a prerequisite for anchors in earthquake retrofitting applications. The dimensions of the existing RC frame structure limited the size of the anchor significantly. Since the depth of the columns was only 20 cm, the maximum possible anchor diameter was 16mm with a related drill hole depth of 125mm.

Figure 12 (Left): HVZ anchor system;

Figure 13:Drilling with template

The resistance of a single anchor was calculated by the concrete capacity design (CCD) method (Fuch, Eigenhausen et. al 1995) which is available as a design guideline in ETAG Annex C (Troonstraat, 1999). As an example, the shear design for the anchorage of the upper beam is shown in the following:

Basic shear resistance of a single anchor HVZ M16 in cracked concrete:

$$V_{Rd,c}^{0} = 5.9kN \tag{1}$$

Shear design according to ETAG Annex C, taking into account spacing s, edge distance c, concrete quality, and load direction:

$$V_{Rd,c} = V_{Rd,c}^{0} \cdot f_{B,V} \cdot f_{\beta,V} \cdot f_{AR,V} \text{ with } c_{\min} = 85mm \tag{2}$$

Influence of the concrete quality $f_{B,V}$:

$$f_{B,V} = 1.0 \text{ for concrete C20/25} \tag{3}$$

Influence of the load direction $f_{\beta,V}$:

$$f_{\beta,V} = 2.0 \text{ for load direction parallel to the concrete edge} \tag{4}$$

Influence of the spacing and edge distance $f_{AR,V}$:

$$\begin{aligned} f_{AR,V} &= \frac{3 \cdot c + s_1 + s_2 + s_3 + \ldots\ldots s_{n-1}}{3 \cdot n \cdot c_{\min}} \cdot \sqrt{\frac{c}{c_{\min}}} \\ &= \frac{3 \cdot 135mm + 20 \cdot 200mm}{3 \cdot 21 \cdot 85mm} \cdot \sqrt{\frac{135mm}{85mm}} = 1.0 \end{aligned} \tag{5}$$

Therefore, the design resistance in shear of one HVZ M16x105 anchor in this application is:

$$V_{Rd,c} = 5.9kN \cdot 1.0 \cdot 2.0 \cdot 1.0 = 11.8kN \tag{6}$$

The CCD method gives a similar procedure to calculate the tensile resistance of the anchors and defines how to take into account the interaction between tensile and shear forces. As the shear link causes a combined tensile and shear action on the beam, a comprehensive design was performed. The design determined that 38 anchors HVZ M16x105 is required to resist the action when the shear link is yielding. Setting of the anchors was performed in the pre-setting mode. This was necessary because of the used HEA 260 profiles. A through setting of the anchors was not possible since the space between the upper and lower flanges of the steel beam is too small to introduce the anchors. In the pre-setting mode the conditions to install the upper steel beam over 38 set anchors was to be considered carefully. Since the clearance of the drilled hole in the steel beams had to be as small as possible in order to guarantee the correct position and alignment of the anchors, a strong focus on the precision of the setting process was required. To guarantee the accuracy of the positioned anchors a special drilling template for each steel beam was produced. This not only provided the exact position of the drill holes, but also a guide to the right direction of the protruding anchor thread. This template consisted two steel plates, separated by struts with the height of the threaded part of the protruding anchor (figure 13).

To transfer the shear loads uniformly over all anchors, the clearance holes were injected with a mortar (figure 14) using the Hilti Dynamic Set (figure 16, see section 3.3). The uniformly distributed shear transfer is necessary to prevent an overloading of a single anchor as well as a cone failure of the related concrete substrate area. In this application, the mortar did not only fill up the clearance holes between the steel beam and the anchor, but at the same time, it served as leveling grout, because it was also injected into the voids between the RC frame substrate and the steel beam.

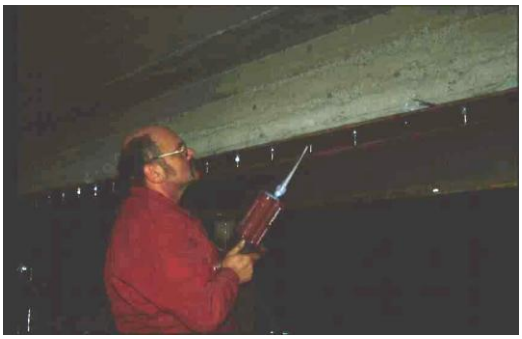

Figure 14: Injecting clearance holes with Hilti HIT HY 150 Mortar

Figure 15 shows the load displacement diagram for the retrofitted structure. The behavior is ductile as intended by the design. Slip was avoided and therefore, the anchor bolts acted fully satisfactorily. In order to avoid slip between the steel frame and the concrete surface, the anchors had to be not only designed correctly but also installed with special precaution as described in section 3.3.

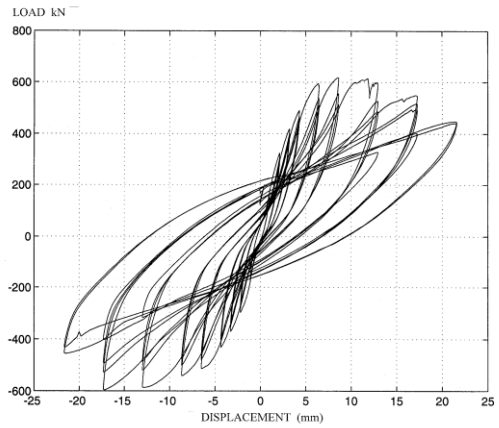

Figure 15: total storey shear force versus storey displacement

2.3 *Distribution of Load to Anchors*

When fixing steel braced frames to the concrete directly, the anchors are set through clearance holes in the frame. Tightening the anchors creates a clamping force between the concrete and the steel frame which permits low level shear forces to be transferred from the concrete to the steel frame via friction. But as higher shear forces are introduced, the friction is overcome and slip will occur between the steel frame and concrete until the first anchor touch its clearance hole and take up more shear force. Since not all anchors are set exactly in the center of their clearance holes, generally the additional shear load will be carried by isolated anchors until all the anchors are in contact with their clearance holes. However, in case of cyclic earthquake loads, these deformations cannot be tolerated; all anchors must take up shear loads from the beginning. If some anchors take load before others, they may be overloaded and fail before the entire system can be loaded. Therefore the so called "Dynamic Set" has been developed (figure 15).

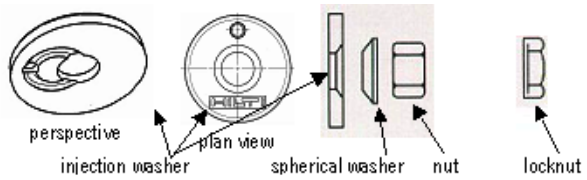

Figure 16: Injection Washer "Dynamic Set"

The dynamic set contains a special washer which allows one to inject the clearance holes between steel frame and the anchors with a mortar. Moreover, the set contains a spherical washer, which ensures that there is no bending in the anchor due to the tightening torque. This fact also improves the anchor behavior under cyclic loads.

Tests have demonstrated that the shear capacity of anchor rows can be significantly improved by injecting the clearance holes. Figure 17 shows the load displacement curves with and without the injected clearance holes subjected to shear loading. With void clearance holes, the loading shows a stiff behavior until the capacity of the concrete edge ahead of the anchor closer to it is reached. Then a concrete cone breaks out in front of the first anchor and the plate slips towards the edge until the anchor behind can take up the load. After a further stiff increase of the load the concrete edge capacity in front of the second anchor is reached. With injected clearance holes both anchors take up load from the start, the premature failure mechanism from the overloading of the concrete edge by the first anchor is avoided and the maximum load is reached directly with very limited displacement.

These tests show that injection of the clearance holes is an efficient means of distributing the loads to all fixing points in cases where only limited displacements can be allowed. When fixing steel braced frames to concrete, the clearance holes should always be filled in order to guarantee a good load displacement behavior. This method can also improve the efficiency of other applications such as fixing steel jackets to concrete columns.

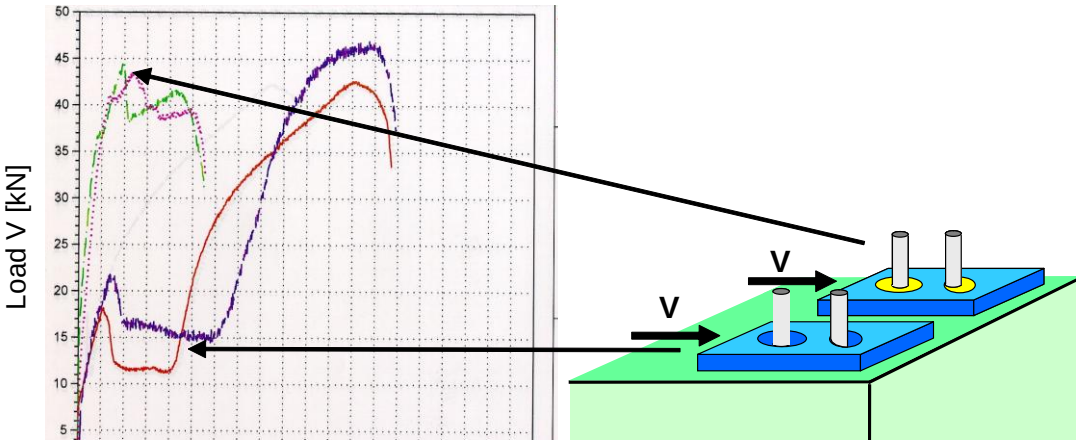

Figure 17: Load-displacement curves for filled and open clearance holes

3 CONCLUSIONS

Two methods to fix steel braced frames to concrete structures have been discussed. The choice of the appropriate method will depend on the conditions of a specific project. For example, the direct connection will be faster in many cases, while the indirect fixing has the advantage that it does not require precision drilling. Costs and availability of materials will also influence the choice.

The indirect connection consisting of adhesive anchors in the concrete, welded studs on the steel braced frame and a mortar joint can be designed according to the design rules for composite steel/concrete structures as given in the relevant structural design codes. Extensive testing has demonstrated that these rules can be applied even if the concrete strength in the structure to be rehabilitated is as low as 5MPa.

The strength of direct connections will be determined according to the rules of anchor design (CCD-method). In order to avoid slip between the steel braced frame and the concrete structure under cyclic earthquake loads, the clearance holes should be filled Tests have shown that the use of injection

washers allows to efficiently distribution of shear loads to all anchors. This technique may well be beneficial not only for fixing steel braced frames to concrete, but in all applications of earthquake strengthening and rehabilitation, where displacements under shear loads should be avoided, for example also when steel jackets are fixed to concrete columns.

REFERENCES:

Yamamoto, Y. 1999 Experimental Research on Bonded Anchor Behavior in Low Strength Concrete and Lightweight Concrete. Research for Hilti AG. Shibaura Institute of Technology, Tokyo.

Cook, R. A., Kunz J. et al. 1998. Behavior and Design of Single Adhesive Anchors under Tensile Load in Uncracked Concrete. *ACI Structural Journal*, V. 95, No. 1,

Kunz, J., Yamamoto Y. et al. 2001. Anchors in Low and High Strength Concrete. *International Symposium on Connections between Steel and Concrete*, Stuttgart

Randl, N. 2007. Load bearing behaviour of shear dowels, *Beton & Stahlbetonbau Special Edition*

Bouwkamp, J., Gomez, S., Pinto, A. et al. 2001. Cyclic Tests on R/C Frame Retrofitted with K-Bracing and Shear Link Dissipator. *European Commission Research Centre*

Fuchs, W.,Eligehausen, R. et al. 1995. Concrete Capacity Design (CCD) Approach for Fastenings to Concrete. *ACI Structural Journal*, Vol. 92, No. 6.

ETAG No 001: Guideline for European Technical Approval of Metal Anchors for Use in Concrete, Annex C: Design Methods for Anchorages. EOTA, rue du Trône 12, Troonstraat, B - 1000 Brussels, 1997