Transactions, **SMiRT-24**
BEXCO, Busan, Korea - August 20-25, 2017
Division VI

Testing and Modelling of Connections with Post-installed Undercut Anchors under Seismic Loading - Assessment of Safety Margins

A. Fäcke[1], F.H. Schlüter[2], F. Borschnek[3], and N. Herrmann[4]

[1] Senior Engineer of SMP Ingenieure im Bauwesen GmbH, Germany
[2] Manager of SMP Ingenieure im Bauwesen GmbH, Germany
[3] Research Engineer, Materials Testing and Research Institute (MPA Karlsruhe), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[4] Vice-President, Materials Testing and Research Institute (MPA Karlsruhe), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

ABSTRACT

Specific undercut anchor types are approved for the subsequent attachment of safety related components in nuclear power plants. These connections are commonly designed for static and dynamic loading conditions based on linear elastic analysis methods. However, in reality the connection behaviour is marked by certain nonlinear effects – in particular at high utilization levels and at accidental loading conditions where cracks may be present in the concrete anchor ground. In general, the use of a linear elastic analysis method at dynamic loading will provide a conservative design in terms of forces. However in terms of predicted displacements the result may not be on the conservative side. In the framework of a Federal Ministry of Economics and Technology (BMWi) sponsored project managed by the project executing part of GRS (Gesellschaft für Anlagen- und Reaktorsicherheit mbH) experimental tests have been performed in order quantify effects coming from nonlinearities, to assess potential safety margins in the design and to assess the influence on displacements at the anchors.

A new setup for the dynamic and cyclic testing of undercut anchors has been developed. This setup considers the complete system of anchors, anchor ground and component. Cracks in the concrete anchor ground can be considered, too. The project is now completed so that all experimental tests have been performed and evaluated. Different types of approved anchors, different loading levels and crack widths have been considered in this work. An overview on the most important numerical and experimental results will be presented. Finally the conclusions in particular with regard to potential safety margins that may be included in the common design practice will be outlined.

INTRODUCTION

The subsequent attachment of safety related pipes and components with metal anchors to reinforced concrete members is a common practice in nuclear power plants. High safety demands have to be imposed on these connections for regular operation as well as for disaster situations including earthquake excitation where large dynamic forces may be accompanied by cracks in concrete. While the static load bearing capacity of metal anchors is a part of approval tests, the behaviour under dynamic loading is not well understood according to the authors' knowledge. There is a need for systematic investigations under realistic conditions with real time dynamic loading. In this context it is necessary to consider the complete system consisting of anchors, the anchor plate and the attached component because effects like shifting of the anchor plate due to regular tolerances and regular limited pull out of anchors in cracked concrete may influence the dynamic response of the system.

The common design procedure of components and their fastening is based on linear elastic behaviour of the component and a rigid fixture. However nonlinear effects like longitudinal and transversal relative movements between anchor and ground as well as between anchor and plate may influence the dynamic behaviour of the system and in turn the forces acting at the anchors. Longitudinal movements are possible when the anchor is slightly pulled out of the concrete. A pull-out of 3 mm is allowed according to design guidelines and can be observed especially when an anchor under tension is located in a concrete crack. Although it is not allowed to place anchors in dissipative zones like plastic hinges even apart of these zones the occurrence of cracks cannot be ruled out during a seismic event. Transversal movements mainly occur due to unavoidable tolerances at the anchor plate holes and due to shifting of anchors at shear loading. These relative movements at the anchors lead to anchor plate sliding, pounding, limited free tilting of the component and dynamic impact loading on the anchor bolt heads.

As part of the research project it was investigated if nonlinear effects have a significant influence on the anchor forces and the dynamic behaviour of the component and in turn on the reliability of common design procedures of fastenings. The investigations were based on the undercut anchors from Hilti and Fischer that have been used for the majority of post installed components. The tests were performed in uncracked and cracked concrete with crack widths ranging from 0.4 mm to 1.5 mm.

An experimental test setup for the dynamic testing of the complete system consisting of component, anchor plate, anchors and concrete fixing ground has been developed. The anchors were tested at a dynamic sinusoidal excitation at different load levels. A “crack frame” was developed so that the anchors were tested also in open cracks. The accelerations, displacements at relevant positions and the forces at the anchors can continuously be monitored. For the design of the test setup a numerical model had been developed that considers the main features of the system.

EXPERIMENTAL TEST SETUP

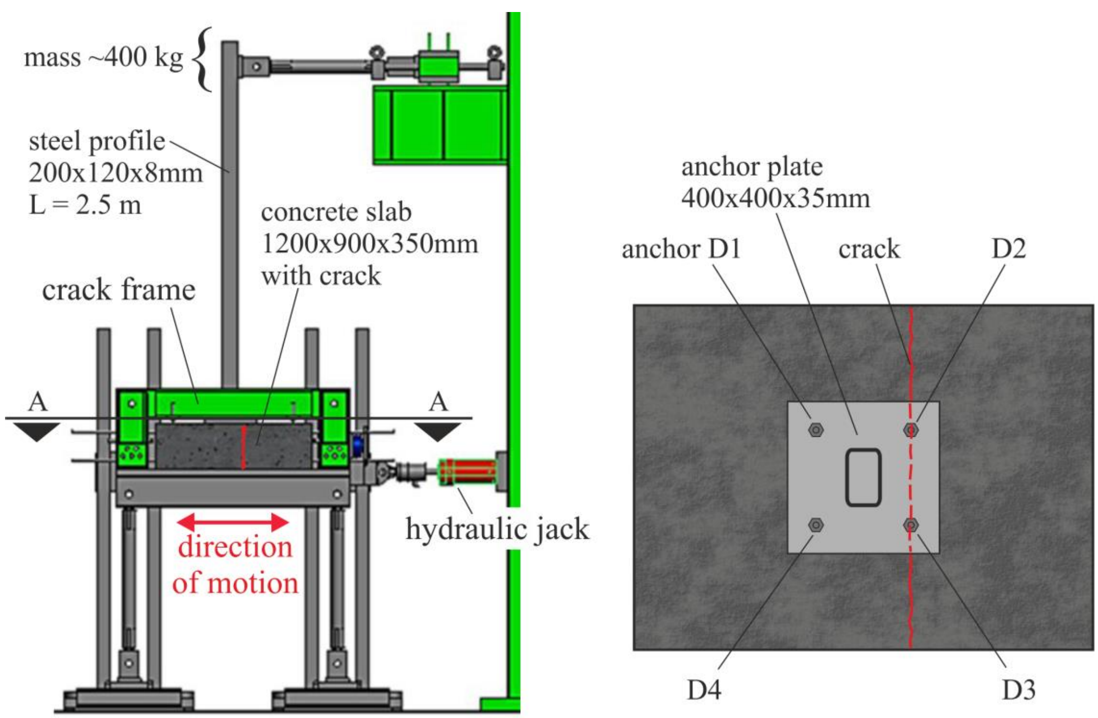

Figure 1. Elevation view of test setup (left) and top view (A-A) on concrete slab with anchor plate (right)

The test setup mainly consists of a horizontally movable concrete slab on which an anchor plate is connected with four undercut anchors. The main dimensions of the setup are shown in figure 1. The component is represented by a steel beam that is welded to the anchor plate and a mass that is indirectly connected on top of the beam. The beam with the mass represents a single degree of freedom oscillator with a theoretical eigenfrequency of 5 Hz assuming a rigid boundary condition at the lower end of the beam. Due to the flexibility of the anchor plate and possible movements at the anchors the frequency of free vibration of the component was actually smaller than 5 Hz in all tests. For this purpose free decay tests have been performed in advance and after each test.

The dynamic excitation of the component was caused indirectly like in a real structure by the anchor ground. For this purpose the concrete slab was forced to a sinusoidal horizontal oscillation by a hydraulic jack. With mobile hydraulic presses a crack can be generated in the concrete slab going through the two anchors at the right side (cp. figure 1). The crack was generated before the tests and its width was kept constant during the test with a ‘crack frame’.

The following undercut anchors that have been used for the majority of post installed components in German nuclear power plants were tested:

- Hilti HDA-T 22-M12x125/50 galvanised version acc. to techn. approval Z-21.1-1987
- Fischer FZA 18 x 80 K M12 galvanised version acc. to techn. approval Z-21.1-1646
- Hilti HDA-T 30-M16x190/40 galvanised version acc. to techn. approval Z-21.1-1987

PRELIMINARY CONSIDERATIONS AND INVESTIGATIONS

The aim of the investigations was to assess the anchor behaviour under dynamic excitation at different utilization ratios. The utilization ratios were defined depending on the anchor resistance acc. to the corresponding technical approvals and the following fundamental design equation of limit state:

$$N_{Ed} \leq N_{Rk}/\gamma_M = N_{Rd} \tag{1}$$

Acc. to the ultimate limit state design (ULS) the load at the anchors should not exceed N_{Ed} respectively N_{Rk}/γ_M which is covered by the first load level. The anchor resistance is controlled by three possible failure mechanisms:

1. pull-out failure ($\rightarrow N_{Rk,p}$) – anchor pull-out of the concrete hole
2. concrete cone failure ($\rightarrow N_{Rk,c}$) –tension failure at a cone shaped surface around the anchor
3. steel failure ($\rightarrow N_{Rk,s}$) – tension failure of the anchor itself

At the selected test setup the pull-out failure was decisive. Hence the design value of the pull-out resistance defines the first load level (table 1, 1st line). The characteristic pull-out resistance forms the second load level (table 1, 2nd line). In order to investigate beyond design performance further load levels were investigated. The third level was the mean resistance of pull-out failure which was assumed to be 30% higher than the characteristic resistance (table 1, 3rd line). The fourth level was the characteristic resistance based on steel failure (table 1, 4th line). The concrete cone failure was not decisive and was therefore not considered any further.

The resistance of undercut anchors based on pull-out failure can be calculated acc. to the technical approvals as follows:

$$N_{Rk,p} = \psi_c \cdot N_{Rk,p,C20/25} \tag{2}$$

While $N_{Rk,p,C20/25}$ is the characteristic pull-out resistance of the anchor in concrete C20/25 and ψ_c is an increase factor to consider an anchorage in concrete with a higher strength. The mean compressive cylinder strength acc. to the material testing was $f_{cm,cube}$ = 52.0 N/mm² with a very small standard deviation. This gives an increase factor of ψ_c = 1.325. The factor of safety for pull out-failure is γ_{Mp} = 1.5 for HDA-T and γ_{Mp} = 1.9 for FZA anchors in the requirement category A2. The requirement category covers accidental design situations like seismic loading acc. to DIN 25449. The resistance $N_{Rk,s}$ based on steel failure can directly be taken from the technical approvals. With the anchor forces and the geometry of the anchor plate it was possible to define the required moment at the anchor plate that had to be reached during the tests. Furthermore with the length of the steel profile the required force respectively acceleration at the mass was known.

Table 1: Test load at different load levels in kN

	Load level	Definition	HDA M12	FZA M12	HDA M16
design	design load at **U**LS	$N_{Rd,p}$	46.4 / 1.5 = 30.9	22.5 / 1.9 = 11.9	93.5 / 1.5 = 62.4
	Characteristic resistance	$N_{Rk,p}$	46.4	22.5	93.5
beyond design [2)]	**M**ean resistance	$1.3 \cdot N_{Rk,p}$	1.3 · 46.4 = 60.3	1.3 · 22.5 = 29.3	1.3 · 93.5 = 121.6 [1)]
	ma**X** load based on steel failure	$N_{Rk,s}$	67	67.4	126 [1)]

[1)] load level not intended to be investigated with the test setup
[2)] here defined as beyond design

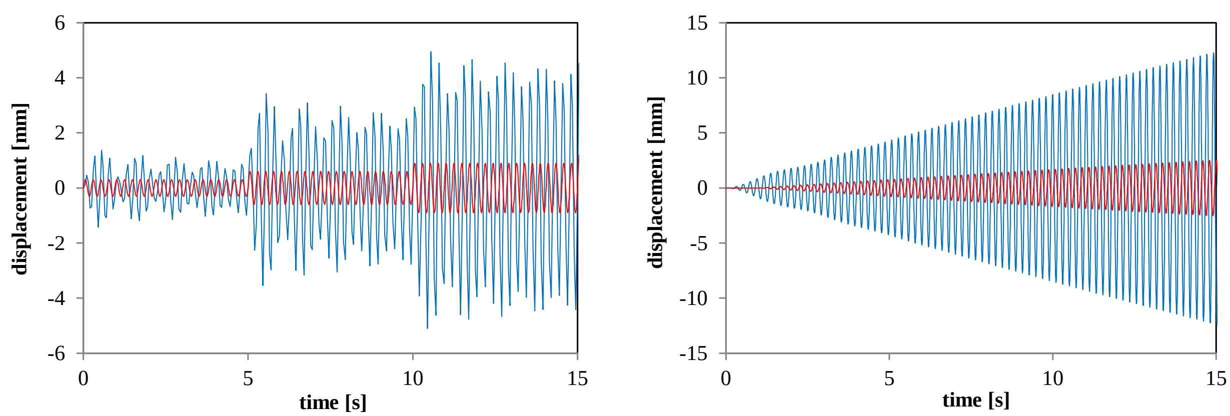

Figure 2. Excitation with step function (left) and continuous function (right) and corresponding responses

The acceleration of the mass is dependent on the relation between circular excitation frequency Ω and circular free vibration frequency of the component ω, the system damping (figure 3) and the amplitude of excitation. Hence the excitation has to be tuned in terms of amplitude and frequency. Initially it was intended to run the test by raising the oscillation amplitude and keep it constant for some cycles at the different load levels. However, the numerical simulations already showed that it is practically not possible to define a time history of excitation that makes it possible to raise and then hold the amplitude without having crucial disturbances in the dynamic answer of the system. Figure 2 (left) shows an example of a time history of excitation with a stepwise increase of the amplitude (red curve). At each step the answer of the system gets greatly disturbed (blue curve). Although it is possible to reduce these disturbances by decreasing the step size and increasing the number of steps, however, then the number of cycles gets to high leading to fatigue loading at the anchors. Finally a time history with a linear increase of the amplitude (figure 2 right) was selected because the answer was linear without disturbances, too. Due to the slow amplitude increase between consecutive cycles the necessity of having constant cycles at the load levels was judged minor.

The preliminary tests were run with a low frequency excitation. That means the frequency of excitation was specified at 90% of the measured free vibration frequency. However, the numerical simulations already revealed that a vertical tolerance at the anchors has a significant effect on the dynamic behaviour of the system. E.g. a vertical tolerance of 1 mm (3 mm) leads to a free vibration frequency decrease at the investigated system at the first load level of HDA-T M12 of 25% (45%) acc. to Fäcke et al. (2015). The effect of the horizontal tolerance is smaller with a decrease of 10% at 3 mm. These tolerances occur unpredictably during test runs mainly due to a progressive pull-out of the anchors. Due to that frequency shift of the system the ratio of Ω/ω increased during the tests and the system ran into resonance (figure 3). Then the loads uncontrollably increased and load levels were skipped. In order to avoid that, a high frequency excitation acc. to figure 3 was selected for the main tests. In this case a frequency shift only resulted in a decrease of loads and the excitation amplitudes hat to be further increased.

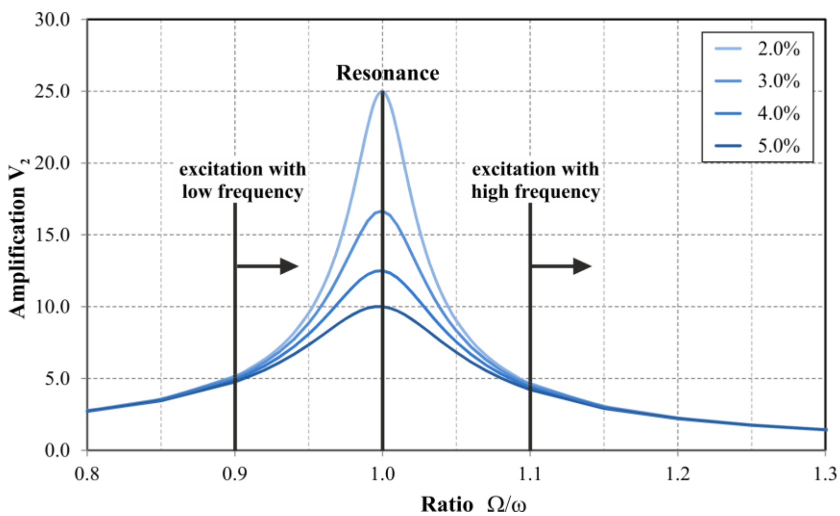

Figure 3. Amplification function for base excitation for different damping ratios in % with the circular frequency of excitations Ω and the circular eigenfrequency ω of the system

EXPERIMENTAL RESULTS

Free decay tests have verified the marked influence of anchor tolerances on the free vibration frequency. Additionally, the damping was determined in the experiments with large crack widths. The results show that the natural frequency and damping of the system is highly dependent on the stiffness of the connection cantilever to concrete block (the anchors in the crack). The conducted experimental tests have shown that the measured natural frequencies were always well below the analytically calculated natural frequencies. Furthermore, the dynamic system behaviour has changed in all experimental setups during the tests. The natural frequency of the system before the conducted tests was always higher than afterwards. This change is clearly the result of the pull-out of the anchors. Furthermore, the damping of the system was generally higher than at a typical system with welded steel profiles. Figure 4 to 6 depict the main results of the tests for the three anchor variants for the crack widths of 0 mm, 0.8 mm and 1.5 mm. The time history of forces at the anchors, vertical displacements (pull-out of the anchors) and horizontal displacements of the anchor plate relative to the concrete slab are shown. In the force diagrams the forces of the load levels acc. to table 1 are superimposed. Table 2 shows the displacements (pull-out) for all tests and load levels.

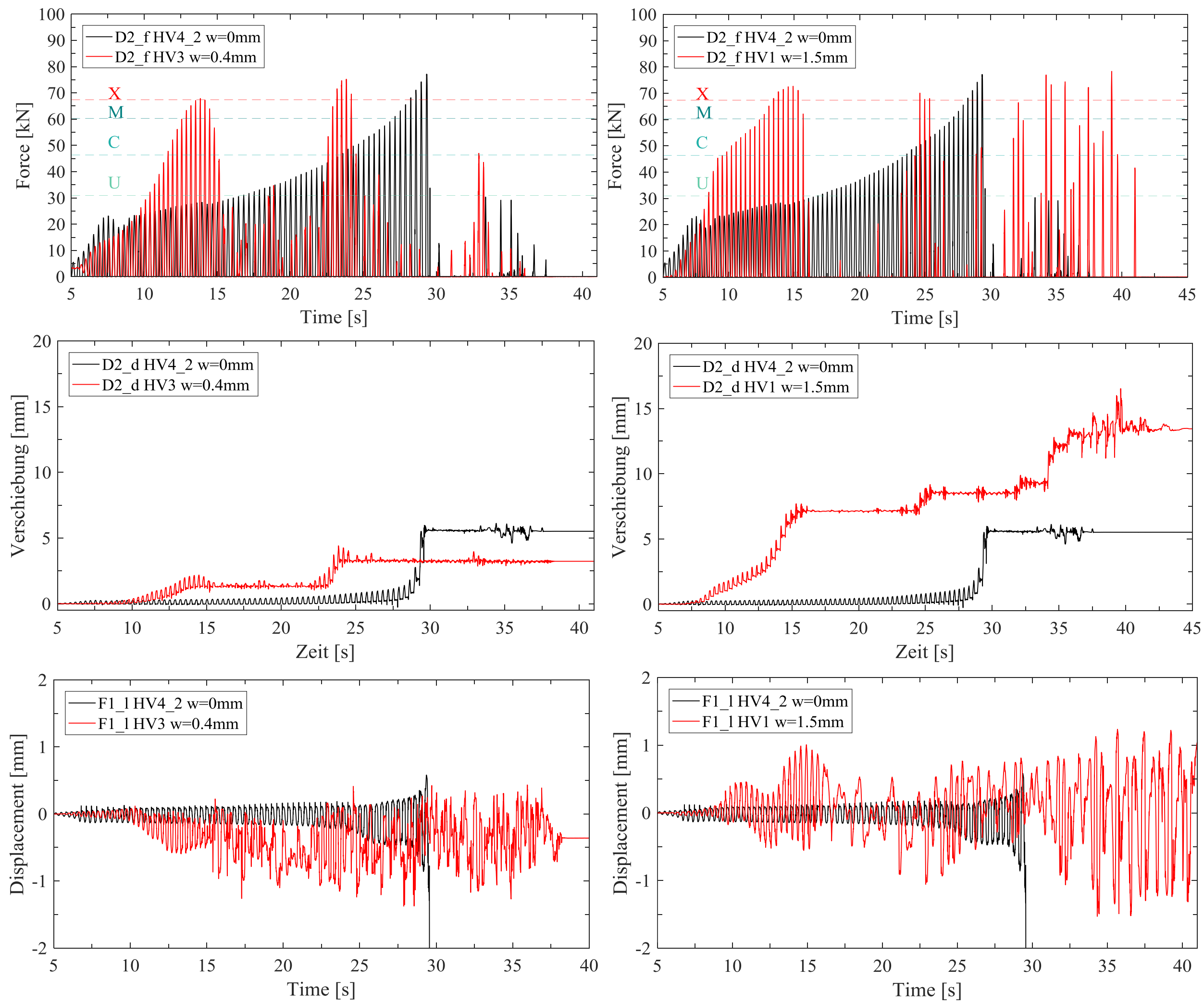

Figure 4. Forces (top), vertical (middle) and hor. displacements (bottom) vs. time at HDA-T M12 anchor D2 for a crack width of w = 0.0 mm in comparison to 0.4 mm (left) and in comparison to 1.5 mm (right).

Figure 4 shows the results for the HDA-T M12 anchor. It can be seen that anchor pull-out is less than 1 mm at the first load level and less than 3 mm at the second load level even at a crack width of 1.5 mm. In all cases the fourth load level could be reached however with a final displacement of 4 mm at a crack width of 1.5 mm. Afterwards the response abruptly decreased because of a frequency shift of the system. After a short period the resistance of the anchors reached the force of the fourth load level again without failure. Hence at design load the anchors performed well with displacements less than 3 mm even at a large crack width. Beyond design level the anchors showed a high robustness with considerable safety margins concerning the resistance in terms of forces. However it must be considered that displacement sensitive components may be harmed and that the frequency of free vibration may drop down and deviate from the eigenfrequency based on elastic behaviour which is generally assumed during design. The horizontal displacements were neglectable with displacements of appr. 1 mm.

Figure 5 shows the results of the FZA M12 anchor. Up to the second load level and a crack width of 0.4 mm the FZA anchor behaves similar to the HDA-T M12 anchor. However after that load level respectively at higher crack widths the displacements (pull-out) lead to a faster frequency shift and drop down of forces. With highly increasing amplitudes of excitation the fourth load level at w ≤ 0.4 mm and the third load level for higher crack widths could still be reached. Although the displacements at the FZA anchors are roughly in a similar range up to design level as at the HDA-T M12 anchors the effect on the frequency shift is more significant. This is because the forces respectively oscillation amplitudes of the component at the corresponding load levels are much lower at the FZA anchors than at the HDA-T anchors. At a nonlinear system, as in the present case, the effect of nonlinearities (here the gap due to pull-out) increases with decreasing oscillation amplitudes. Beyond design level and at high crack widths the displacements increased up to 13.5 mm. Summarising the above, it can be said, that the FZA anchors have a relative high robustness in terms of force resistance, too. However the performance in terms of displacements (pull-out) is less advantageous leading to a higher change in the system behaviour.

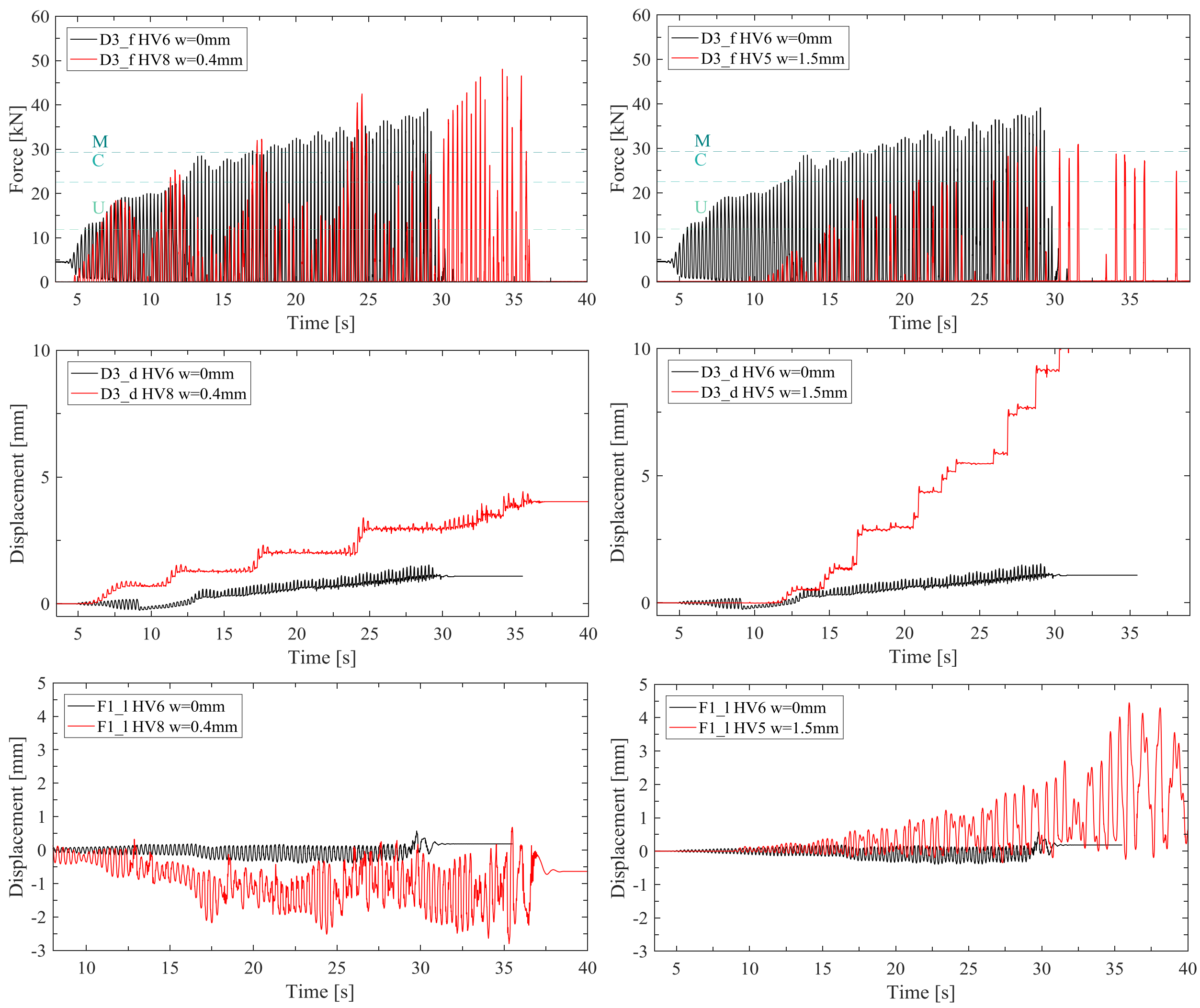

Figure 5. Forces (top), vertical (middle) and hor. displacements (bottom) vs. time at FZA M12 anchor D3 for a crack width of w = 0.0 mm in comparison to 0.4 mm (left) and in comparison to 1.5 mm (right).

The experimental results for the HDA-T M16 anchor are depicted in figure 6. Due to the limitation of the test setup the upper load levels could not be reached. The second load level was reached at w = 0.0 mm and almost reached for higher crack widths. The anchors showed a stable performance up to the maximum reached load at all tests. The displacements up to the tested loads were comparable to the displacements at corresponding load levels at the HDA-T M12 anchors. No validated conclusions can be drawn for beyond design levels however based on the good performance up to the tested load levels it is rather probable that the HDA-T M16 anchors have a significant safety margin, too.

Table 2 summarizes all test results in terms of vertical displacements (pull-out) at the tested load levels for the anchors D1 and D4 that were not within the crack and for the anchors D2 and D3 that were within the crack. A limited pull-out of 3 mm is allowed according to the ETAG-001 guidelines. This limitation was fulfilled for all crack widths up to the second load level for the HDA-T M12 and M16 and up to the first load level at the FZA M12.

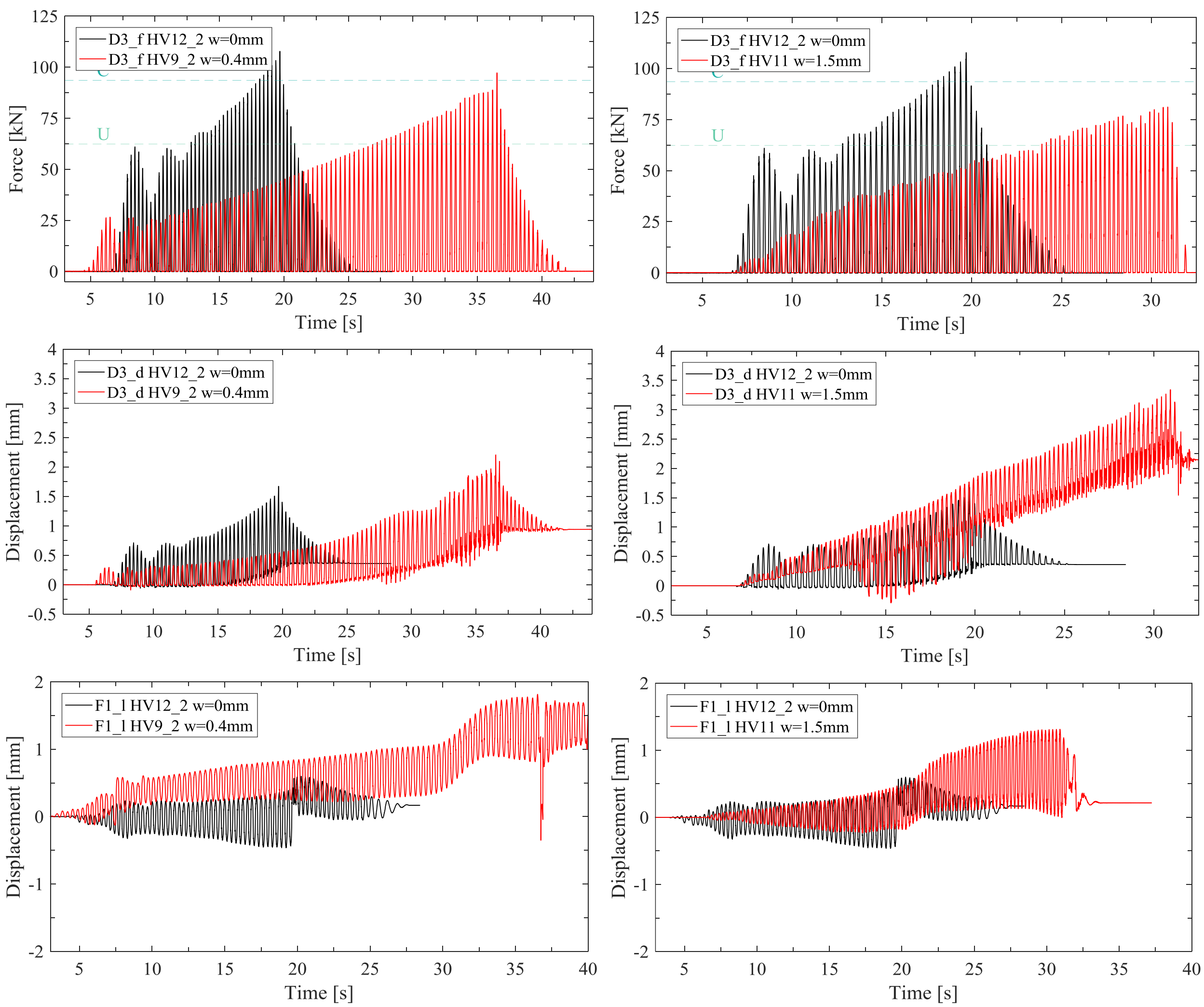

Figure 6. Forces (top), vertical (middle) and hor. displacements (bottom) vs. time at HDA-T M16 anchor D3 for a crack width of w = 0.0 mm in comparison to 0.4 mm (left) and in comparison to 1.5 mm (right).

Table 2: Vertical displacements of anchors (pull-out) at the investigated load levels

		HDA M12				FAZ M12				HDA M16	
		U	C	M	X	U	C	M	X	U	C
w = 0.0 mm	D1	0.52	0.78	1.18	1.46	0.03	0.15	0.66	-	0.76	1.20
	D2	0.35	0.66	1.04	1.26	0.02	1.16	0.00	-	0.90	0.00
	D3	0.41	0.68	1.05	1.36	0.06	0.07	0.68	-	0.72	1.29
	D4	0.70	1.07	1.62	2.05	0.00	0.88	0.00	-	0.64	1.17
w = 0.4 mm	D1	0.41	0.81	1.49	1.83	0.06	0.40	0.73	-	0.82	1.47
	D2	0.43	0.97	1.33	1.96	0.48	1.59	3.24	-	0.84	1.48
	D3	0.80	1.29	1.88	2.68	0.29	1.15	1.91	-	0.99	1.75
	D4	0.39	0.72	1.10	1.42	0.07	0.20	0.55	-	0.70	1.39
w = 0.8 mm	D1	0.88	2.06	2.99	3.67	0.00	0.32	0.77	-	0.42	0.78
	D2	1.45	1.97	2.64	3.24	0.34	0.90	1.52	-	1.80	0.00
	D3	0.55	1.13	2.20	2.42	0.74	3.22	4.29	-	1.25	2.46
	D4	0.41	0.70	1.07	1.36	0.06	0.33	1.13	-	0.70	0.00
w = 1.5 mm	D1	0.68	1.00	1.45	1.75	0.04	0.14	0.24	-	0.77	0.00
	D2	0.59	1.47	3.07	4.03	1.78	4.28	13.5	-	2.47	0.00
	D3	1.22	2.36	7.76	0.00	1.19	4.11	8.59	-	2.23	0.00
	D4	0.56	0.89	1.34	1.62	0.03	0.20	0.57	-	0.86	1.54

CONCLUSION

The tests of a post installed component connected with different undercut anchors to a dynamically moving concrete slab have been successfully performed. Free decay tests have shown that the measured natural frequencies were always well below the analytically calculated natural frequencies of the component and damping was usually higher than in a system with welded steel profiles. This is mainly due to a flexibility of the anchor plate and nonlinearities in the system coming from displacements (pull-out) of the anchors.

At the tests with the HDA-T M12 the maximum load level (theoretical steel failure) could be reached at all tests with crack widths up to 1.5 mm. Up to design level (loading up to the characteristic pull-out resistance of the anchors) the displacements (pull-out) were less than 2.36 mm. For beyond design level (up to the theoretical steel failure) the displacements went up to 4.03 mm. At beyond design level the anchors showed a high robustness with considerable safety margins concerning the resistance in terms of forces. However it must be considered that displacement sensitive components may be harmed and that the frequency of free vibration may further drop down and deviate from the eigenfrequency based on elastic behaviour which is generally assumed during design.

The behaviour of the FZA M12 anchors up to design load level and a crack width of 0.4 mm was similar to the HDA-T M12 anchor. However after that load level respectively at higher crack widths the displacements (pull-out) were more pronounced and led to a faster frequency shift and drop down of forces. Due to the higher displacements the maximum load level could not be reached in all tests. However all anchors have reached at least the third load level (mean pull-out resistance). Hence the FZA anchors have a relative high robustness in terms of force resistance, too. However the performance in terms of displacements (pull-out) is less advantageous leading to a higher change in the system behaviour.

Due to the limitation of the test setup the upper load levels could not be reached at the HDA-T M16 anchors. However the design load was almost reached at all tests. The anchors showed a stable performance up to the reached load level at all tests. The displacements up to the tested loads were comparable to the corresponding displacements at the HDA-T M12 anchors. Although no validated conclusions can be drawn for beyond design levels, based on the good performance up to the tested load level it is rather probable that the HDA-T M16 anchors have a significant safety margin, too.

REFERENCES

Faecke, A., Schlüter, F.H., Herrmann, N., and Mueller, H.S. (2013). *A NEW TESTING SETUP FOR ANCHOR BOLT CONNECTIONS UNDER DYNAMIC EARTHQUAKE LOADING*, SMIRT-22 18-24 Aug., San Francisco, USA.

Faecke, A., Schlüter, F.H., Borschnek, F., Herrmann, N., and Mueller, H.S. (2015). *A TESTING SETUP FOR ANCHOR BOLT CONNECTIONS FOR REALTIME DYNAMIC LOADING*, SMIRT-23 10-14 Aug., Manchester, UK.

ETAG 001 “Guideline for European Technical Approval of Metal Anchors for use in Concrete”, Part 1 “General” (Edition 1997, endorsed 2007)

ETAG 001 “Guideline for European Technical Approval of Metal Anchors for use in Concrete”, Part 3 “Undercut Anchors” (Edition 1997, endorsed 2010)

ETAG 001 “Guideline for European Technical Approval of Metal Anchors for use in Concrete”, Annex C “Design Methods for Anchorages” (Edition 1997, endorsed 2010)

DIBt Leitfaden 2010, Leitfaden für Dübelverbindungen in Kernkraftwerken und anderen kerntechnischen Anlagen, Deutsches Institut für Bautechnik, June 2010

Z-21.1-1987 German Technical Approval from DIBt: Hilti Hinterschnittdübel HDA KKW für die Befestigung in Kernkraftwerken und kerntechnischen Anlagen, period of validity 2013 - 2018.

Z-21.1-1646 German Technical Approval from DIBt: Fischer-Zykon-Anker FZA für außergewöhnliche Einwirkungen, validity until 2013.

DIN 25449 “Reinforced and prestressed concrete components in nuclear facilities - Safety concept, actions, design and construction”, June 2009