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Plasticity of anchors in damaged by earthquake concrete base

Mikhail Kovalev* and *Oleg* Kabantsev

Moscow State University of Civil Engineering, Yaroslavskoye shosse, 26, 129337, Moscow, Russia

Abstract. Most frequently used types of anchors were subjected to experimental studies to obtain valid data on post-installed anchors, such as mechanical anchors (wedge expansion anchors, undercut anchors); bonded anchors (with epoxy resin) and bent cast-in-place anchors. The authors studied the effect of an earthquake-induced damage (plastic deformation) of a concrete base and multi-cyclic dynamic loads, similar to seismic ones, on plasticity of anchors. Plastic phase deformation in case of reinforced concrete base was simulated as a system of cracks of different opening width. The results of the research show that increase in the width of the crack opening from 1.5 to 3.0 mm leads to a decrease in the values of the plasticity factors. Dynamic loading does not lead to a significant change in the plasticity factor related to static loading for all failure mechanisms, except for the bond failure. On the base of obtained results reduction factors of seismic loads may be determined for further calculation of anchor joints subjected to seismic impact.

1 Introduction

Calculation and design principles for load-bearing systems of earthquake-resistant buildings were developed more than half a century ago [1] and set the foundation for most regulatory documents in the field of seismic-resistant building construction. The regulatory basis of load-bearing ability of a structure with given plastic deformation level is plasticity factor (μ) which is general structure characteristic.

For a vast range of structures, the most widely used method of plasticity coefficient determination, being well theoretically and experimentally confirmed [2], is the relation of total permissible deformation (ε_{tot}) to value of elastic part of deformation (ε_{el}).

Permissible values of plasticity factor are based on results of experimental researches in which the features of structure deformations are investigated for a full range of loads – up to fracture. In this case the most significant results may be obtained at high-cycle loading which corresponds to seismic effect with sufficient reliability [3,4].

Studies of plasticity coefficient determination were carried out mostly for typical load-bearing structures used in seismic-resistant systems of a building – structures made of reinforced concrete, brickworks, steel and etc. However, development of constructure industry creates new types of building structures and their elements that have not been

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* Corresponding author: kovalyov.mike@gmail.com

studied for plasticity behavior at static and dynamic loadings. Anchors are one of those structure elements.

Anchors are most widely used as fasteners of structures and equipment to basements of different materials. Some individual structure elements that are part of a supporting system of a building, engineering equipment or nonstructural elements are fastened with anchors. According to the method of installing anchors are divided into two groups: cast-in-situ and post-installed anchors.

One of the most important tasks is to investigate influence of base condition damaged by earthquake on anchor plasticity. As shown above, traditional way to design seismic-resistant buildings is based on the assumption of plastic phase deformation occurrence which in case of reinforced concrete base is displayed as a system of cracks of different opening width. The most conservative situation is the crack formation in the anchor installation area. Possibility of this case is confirmed by a number of studies [5,6]. In European [7,8] and American [9,10] regulatory documents for anchor seismic test crack opening width is 0,8 mm. This value is based on the numerical simulation carried out in [11] on the basis of prohibition of anchor installation in area of possible plastic hinge appearance. However, there is a number of studies [12-14] in which greater values (up to 1,5 mm) of required crack opening width are substantiated for anchor tests. In [15] it is shown that there are requirements for ultimate permissible crack opening width in structures subjected to seismic loading set by regulatory documents. For design earthquake there is a design point that corresponds to insignificant crack opening. Such structure condition after earthquake in a number of regulatory documents (for example, [16]), is called Immediate Occupancy Level (IOL) and ultimate crack opening width should not exceed 1,5 mm. For a reference earthquake there are design purposes that corresponds to higher permissible crack opening width. Such structure condition after earthquake is called Life Safety Level (LSL) and ultimate crack opening width should not exceed 3,0 mm.

On the base of obtained results reduction factors of seismic loads may be determined for further calculation of anchor joints subjected to seismic impact.

2 Methods and materials

Tests were carried out for anchors shown in table 1. Anchors were embedded in concrete blocks with grade C30/37.

Table 1. Types of tested anchors.

№	Type of anchor	Anchor	Anchor diameter d, mm	Hole diameter, mm	Effective embedment depth h_{ef}, mm
1	Cast-in-place anchors	Bent anchor bolts [17]	M16	-	150-250
			M36		410-540
2	Post-installed anchors	Mechanical undercut anchors Hilti HDA-T	M12	22,3	125
			M20	37,4	250
3		Mechanical extension anchor Hilti HST3	M12	12,3	70
			M20	20,4	101
4		Bonded anchor Hilti HIT-RE500V3 with threaded rods	M12	14,3	70
			M20	22,4	100

Experimental research of anchors was done with tensile static and multi-cyclic dynamic loads. Anchor displacement relative to concrete base was measured using external linear transducer. Figure 1 shows anchor loading setup.

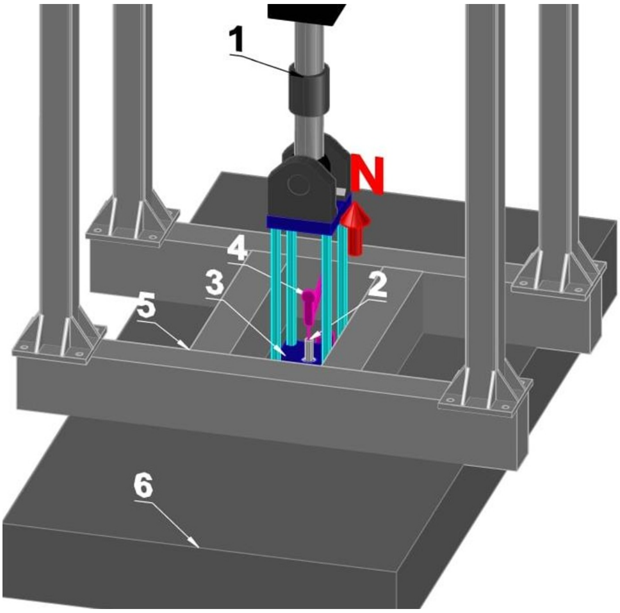

Fig. 1. Anchor loading setup. – 1 – hydraulic jack, 2 – anchor, 3 – fixture, 4 – displacement transducer, 5 – loading rig, 6 – concrete base

Seismic loading was simulated by multi-cyclic dynamic loading according to ETAG001 [8].

Plasticity factor values were determined using formula:

$$\mu = 0{,}85\Delta_{max}/\Delta_{el}, \qquad (1)$$

where Δ_{max} – anchor displacement at ultimate load; Δ_{el} – anchor displacement at the end of elastic stage.

3 Results

Test results show that anchors in concrete base realize four failure mechanisms: anchor steel failure, concrete base cone failure, pullout failure and bond failure (for bonded anchors). (figure 2).

(a) (b)

(c) (d)

Fig. 2. Failure mechanisms for anchorages: a) steel failure; b) concrete cone failure; c) pullout failure; d) bond failure

Studies have established that embedded anchors implement two main types of failure mechanisms: anchor material (steel) failure and base concrete cone failure. The type of failure mechanism is determined by the embedment depth of the anchor and the strength characteristics of concrete and the anchor material. The performed studies have established that there is a certain threshold value for the installation depth of embedded anchors, at which the strength of anchoring in concrete exceeds the strength of the anchor material. At installation depths equal to or exceeding the threshold value, the failure of the anchor fastening occurs by the anchor material. At installation depths less than the threshold value, the failure of the anchor occurs by the base concrete with the formation of a cone. For type 1 anchor with a diameter of M16 the established threshold depth was 200 mm, for an anchor with a diameter of M36 – 440 mm.

Post-installed anchors implement all four types of failure mechanisms shown above. Due to the fact that the installation depth of the anchor is specified by the manufacturer, the failure mechanism depends on the type of anchor, grade of the concrete base and the width of the crack opening in the base. Table 3 shows failure mechanisms of post-installed anchors installed, depending on the type of anchor fastening.

Table 2. Failure mechanisms for post-installed anchors

Anchor type	d, mm	Series mark	h_{ef}, mm	Steel strength, MPa	Concrete grade	Failure mechanism at crack width				
						0 mm	0,4 mm	0,8 mm	1,5 mm	3,0 mm
2	12	2-12	125	800	C30/37	1	1	1	1	3
	20	2-20	250			1	1	1	1	3
3	12	3-12	70			2+4	2+4	2	2	2
	20	3-20	101			2+4	2+4	2	2	2
4	12	4-12	60	1000		3				
	20	4-20	100			3				

Failure mechanisms designation: 1 – steel failure; 2 – pullout failure; 3 – bond failure; 4 – concrete cone failure.

4 Discussion

Plasticity factors calculated for different types of anchors are shown in table 3. Figure 3 shows plasticity comparison for different types of failure mechanism.

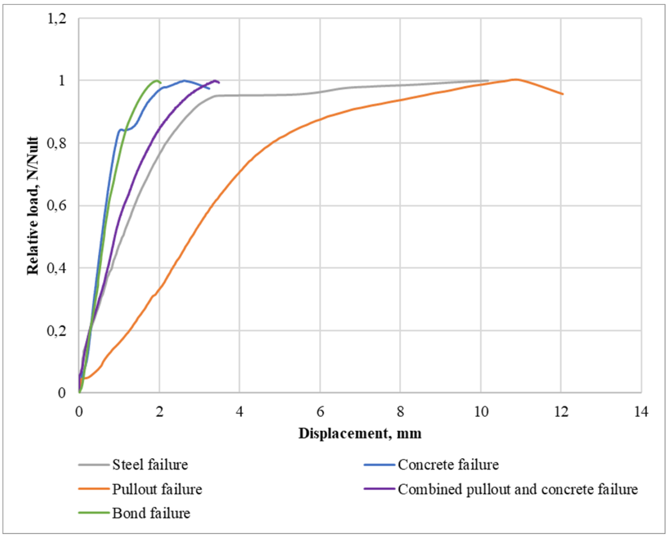

Fig. 3. Characteristic relative load – displacement diagrams for different failure mechanism

Table 3. Plasticity factors for anchors in damaged concrete base

Anchor type	d, mm	h_{ef}, mm	Crack width, mm	Failure mechanism	Type of failure mechanism	Plasticity factor μ	
						Static loading	Dynamic loading
1	16	150	1,5	4	Elastic brittle	1,3	1,2
	16	200	1,5	1	Elastoplastic	4,7	4,5
	36	500	1,5	4	Elastic brittle	1,4	1,2
	36	580	1,5	1	Elastoplastic	4,1	4,0
2	12	125	1,5	1	Elastoplastic	3,9	3,8
			3,0	2	Elastoplastic	3,4	3,2
	20	250	1,5	1	Elastoplastic	4,3	4,4
			3,0	2	Elastoplastic	3,6	3,3
3	12	70	1,5	2	Elastoplastic	2,4	1,9
			3,0	2	Elastoplastic	1,9	1,7
	20	101	1,5	2	Elastoplastic	2,6	2,2
			3,0	2	Elastoplastic	2,2	2,0
4	12	60	1,5	3	Elastic brittle/ elastoplastic	1,2	3,2
			3,0	3	Elastic brittle/ elastoplastic	1,0	2,7
	20	100	1,5	3	Elastic brittle/ elastoplastic	1,3	3,4
			3,0	3	Elastic brittle/ elastoplastic	1,1	3,0

Failure mechanisms designation: 1 – steel failure; 2 – pullout failure; 3 – bond failure; 4 – concrete cone failure.

5 Conclusion

Based on the processing of research results, the values of plasticity factors μ for various types of anchor fastenings and their failure mechanisms were determined. An increase in the width of the crack opening from 1.5 to 3.0 mm leads to a decrease in the values of the plasticity factors. Dynamic loading does not lead to a significant change in the plasticity factor related to static loading for all failure mechanisms, except for the bond failure. The bond failure mechanism is characterized by a transition from an elastic-brittle mechanism under static loading to an elastoplastic mechanism under dynamic loading. Seismic load reduction factors can be determined for subsequent calculations of anchors under seismic actions based on the obtained results.

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