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Performance-based design method of steel-to-concrete post-installed connection under combined action of earthquake and fire

Performance-based design method of steel-to-concrete post-installed connection under combined action of earthquake and fire

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Abstract. ABAQUS software was first used to study the structure behaviour of steel-to-concrete connection by post-installed anchorage under cyclic loading. Three types of embedment depth 25d, 20d and 15d were considered. Based on previous simulation results of earthquake and fire, it can be concluded that the seismic performance of steel-to-concrete connection by post-installed anchorage is strongly related to the rotation angle θ of steel beam. The heat analysis results indicate that the fire resistance of post-installed connection after 2 hours exposure could meet the requirement of related codes. Based on the simulation results mentioned above, a performance-based design conception with four performance levels has been provided to guarantee structure safety under the combined action of earthquake and fire. According to the principle of performance-based methodology, rotation angle θ of steel beam and fire resistance rating T are chosen as critical index for performance evaluation. Among the 4 levels of performance, Level 1 has the highest specification for disaster protection. To achieve the performance level 1, the thickness of fire protection layer should not be less than 45 mm, and the embedment depth should be 25d at least.

1. Introduction

In order to overcome the problems of aging buildings, some engineers have resorted to structural redevelopment using correctional methods to increase the performance of buildings. Thus, the use of post-installed system has been one of the most effective methods used [1]. Post-installed anchorage system is based on transferring the applied load from the anchored steel element, through the adhesive layer, to the concrete along the entire bonded surface [2]. Makoto Obata, has shown that a bond type anchor bolt can also be used in the concrete-steel assembly with almost similar results, even though their failure mode is important [3]. This discovery can enhance the ability of a structure to meet the different functional requirements of dual-disasters accidents such as earthquake and fire. Dongpo Wang and Dongsheng Wu tested the force of extraction required for post-installed anchor with large diameters in concrete foundations [4]. Paganoni has shown that structural connections are crucial for determining seismic behaviour in buildings, design codes recognize their importance, both in the case of modern buildings and ancestral structures [5]. Bassam A.Tayeh has studied pull-out behaviour of post-installed rebar connection using chemical adhesives and cement based binders , the results showed that the use of adhesives and UHPCC(mortar, ultra-high performance self-compacting concrete) extraction load values were very close.

The specimens attached to the mortar were exceeded [5, 6]. Note that some post-installed anchor systems have been studied to determine their technical qualifications in seismic zones in Europe [7].

Francisco González has shown that the installation conditions of anchorage can significantly affect the strength of anchorage [8]. However, all these facts constitute a certain limitation because several elements of structure each taken from its side are likely to provide more important and innovative information.

In order to solve this problem, in this research, a performance-based design of post-installed anchorage has been studied. This is an effective method for adopting the concept of performance, proposing performance objectives and determining the level of performance and specific parameters. This approach differs from existing methods in that different performance targets can be determined by modifying quantitative indicators such as embedment depth and the thickness of fire protection layer. In the following parts of this article, numerical analyses of fire behaviour, earthquake as well as test results and levels of performances are presented.

2. Performance-based Design of Post-installed Anchorage

In order to make the post-installed joint meet different functional requirements under the dual disasters of earthquake and fire, it is an effective method to adopt the performance-based design concept, propose performance targets, and determine the performance level and specific parameters. The designed performance of joint at the post-installed anchorage is taken into consideration such as deformation, bearing capacity, fire prevention measures and damage conditions. Different performance targets can be determined by modifying the quantitative indicators such as embedment depth and the thickness of fire protection layer. Different from the performance-based design method of complete structure, the performance goals and performance levels of post-installed joint can be considered from the two aspects of seismic resistance and fire resistance.

2.1. Numerical Analysis of Seismic behavior

Based on the above analysis, in order to study the seismic performance of steel-to-concrete post-installed joints, ABAQUS software was first used for simulation analysis under cyclic loading. During the earthquake simulation of the structure, all the constituent elements were solicited especially the connection joints that constituted the point of failure of steel-to-concrete post installed. Consequently, this leads to a considerable reduction in its carrying capacity. Under the effect of even larger and present loads, the whole structure could not resist any longer. The analysis were mainly conducted on different embedment depths 25d, 20d, and 15d, respectively. During the whole low-cycle repeated loading process, the rotation angle of the steel beam is closely related to the force performance of the rear anchoring joint, and the force-angle curve is drawn to mark the key state. The simulation results showed that the rotation angles of I-shaped steel beams were 0.00247, 0.002488, and 0.00252 for three types of embedment depth respectively, when bonded-in rebar yielded. The angles were 0.017, 0.0173, and 0.0198 respectively, for the state of peak load. While the maximum angles were 0.0348, 0.0267, and 0.0227 at the failure state. It reveals a clear connection between the steel beam's rotation angle and the performance of post-installed joint.

For joints with different embedment depth, it was concluded that the rotation angles corresponding to rebar yielding are basically same. After then the deformation capacity would enhance with longer embedment depth, therefore it is possible to define different performance levels and damage conditions as a key indicators.

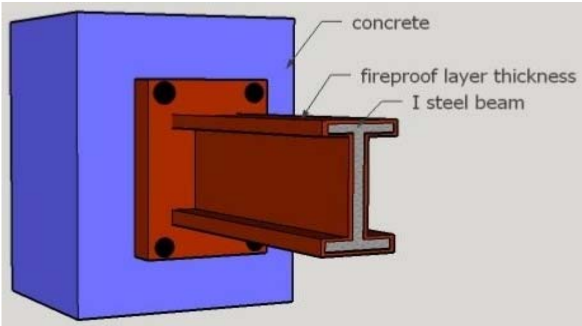

Figure 1. 3D Model（concrete, fireproof layer, steel plate, steel beam）

2.2. Numerical Analysis of Fire behavior

The finite element simulation was carried out for steel-to-concrete post-installed joints under high temperature performance. The ISO834 standard curve was adopted. According to the existing research results, adhesive temperature has significant influence on the anchorage behaviour, and most scholars have pointed out that when the adhesive temperature exceeded 400°C, the bond performance will greatly reduce and the anchor was not suitable for load bearing any longer. Therefore, the time when the rebar temperature reaches 400°C could be set as the fire resistance limit. In order to ensure the structural safety of post-installed joint after fire exposure, the residual strength of joint after high temperature was analysed.

In order to improve the corrosion durability of the structure, ECC has been applied to steel. Engineered Cementitious Composite (ECC) for short is a new material using ingredients similar to fiber reinforced concrete. It consists of water, sand, fiber, cement and some common chemical additives. ECC does not use a lot of fiber unlike same fiber materials. In general, 2% or less by volume of discontinuous fiber is sufficient. Depending on elements making up the matrix, ECC has a variant compressive strength of 30 to 70Mpa. Some additional potential applications of ECC are for high energy absorption structures, such as dampers, joints for steel elements. Thus all these structures subjected to loads and at a high temperature can take advantage of the isotropic energy absorption behaviour of ECC.

In sequential fire simulation, the model configuration and size are entirely same with that of seismic model. 8 kinds of fireproof layers thicknesses, such as-25mm, 30mm, 35mm, 40mm, 45mm, 50mm, 55mm, and 60mm, are taken into account. According to the existing requirements for fire-resistance limit, the fire exposure time in the simulation is 2 hours. The maximum temperatures of bonded-in rebar under different fireproof layer thickness are listed in Table 1, and the time-history curves of rebar temperatures have been compared in Fig.2.

Table 1. Main result of fire simulation

Number	Fireproof layer thickness(mm)	Maximum temperature of bonded-in rebar(°C)	Fire resistance limit (min)
1	25	514	80
2	30	494	106
3	35	450	130
4	40	410	145
5	45	394	120
6	50	350	120
7	55	303	120
8	60	298	120

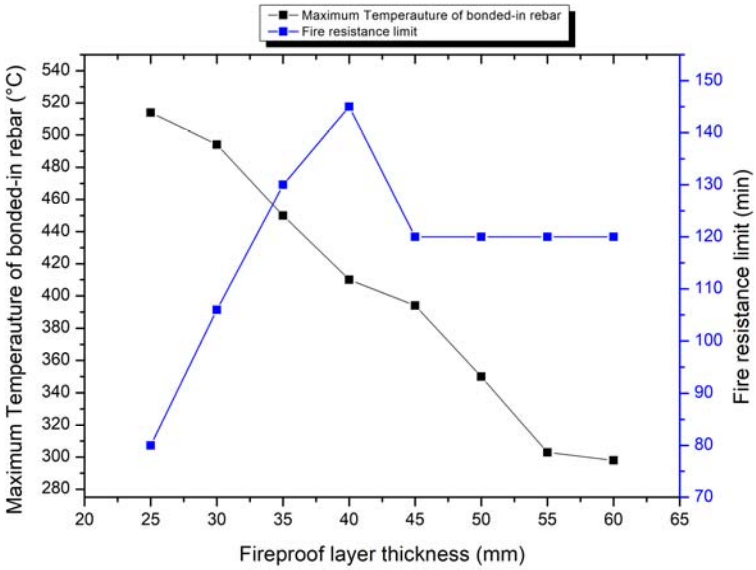

Figure 2: Fire simulation curves

In order to improve fire performance of steel-to-concrete post-installed, 8kinds of fireproof layers thickness such as 25mm, 30mm, 35mm, 40mm, 45mm, 50mm, 55mm and 60mm are taken into account. Figure 3 shows that after the exposure of steel to fire, the time limit of resistance of steel is 2h when the fireproof layer thickness is at least 45 mm at a given temperature. This is expressed in the diagram by the constancy or the straight line appearing on the curve of fire resistance limit.

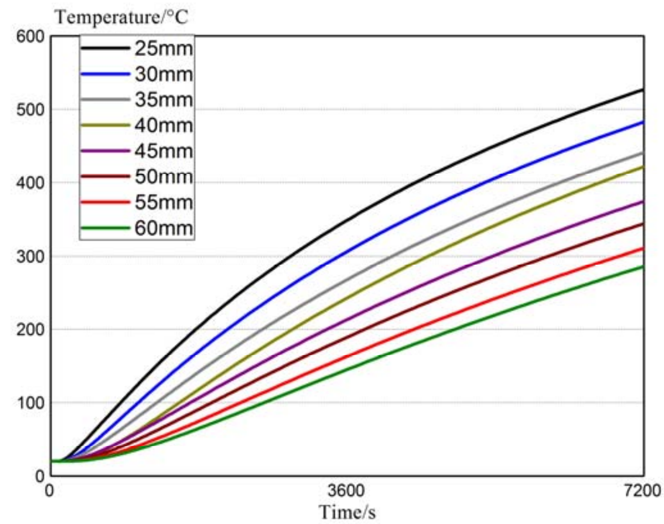

Figure 3: Temperature history curves for different fireproof thickness

2.3. Definition of Performance Levels

Based on the above simulation results of earthquake and fire, it can be concluded that the seismic performance of steel-to-concrete post-installed joint is strongly related to the rotation angle of steel beam. And the rotation angle θ at rebar yield can be set as the reference value, and two indices, peak rotation coefficient R_p and ultimate rotation coefficient R_u which are the ratio of rotation angle in peak load θ_p to θ and the ratio of rotation angle in ultimate state θ_u to θ respectively, have been defined to evaluate the deformation capacity of joint. According to the relationship between the temperature development and the residual bearing capacity after fire exposure, as well as the fire resistance performance index, the fire resistance limit and the damage degree of fire protection layer), according to the different requirements of seismic strength and fire protection of post-anchored joints, the performance levels of post-installed joint under earthquake and fire coupling action could be defined in four types.

It should be noted that this performance design does not consider the coupling effect between earthquake and fire, that is, the performance analysis under the action of single disaster.The performance level 1 describes the deformation state of joint in which rotation angle at peak load is less than 7θ(θ is the rotation angle at rebar yield) , and the ultimate rotation angle is more than 14θ.Under such performance level, the post-installed joint presents excellent seismic behavior and satisfactory fire resistance capacities. Also 2-hour fire resistance rating could absolutely meet the regulation stated in the "Code for the Design of Building Fire Protection". Therefore the level 1 is the highest performance level.

To achieve the performance level 1, the thickness of fire protection layer should not be less than 45 mm, and the embedment depth should be more than 25d. The residual capacity decreased by approximately 17.5% after high temperature. Important structures or equipment can be designed with the goal of this performance level.For performance level 2, it has the same deformation capacity at peak load with level 1 while the ultimate rotation angle is defined in the range of 10θ-14θ. Which indicates that the corresponding seismic performance and deformation capacity are lower than that of level 1, and the fire resistance limit is between 1.5-2 hours. To achieve this performance level, the thickness of fireproof layer is generally 35mm-45mm, and the embedment depth is not less than 20d. The residual capacity drops by about 40% after fire exposure. The common post-installed anchorage connection should be designed to meet such performance level requirements.

In performance level 3, the rotation angle of steel beam is greater than 7θ under peak load, and the maximum rotation angle is in the range of 7θ-10θ, while the fire resistance rating is about 1-1.5 hours. Compared with level 1 and level 2 , the deformation capacity and fire resistance of joint in level 3 are significantly reduces. After fire exposure, the residual capacity decreases to 50% below. When the thickness of fireproof layer is less than 35mm and the embedment depth is 15d, the post-installed joint would probably show the structural behavior of similar to the performance level 3.

The seismic performance and fire resistance of post-installed joint in performance level 4 are the poorest one and far lower than the other three levels. Such performance level could only be applicable to temporary or not life-threatening structures. The corresponding fire protection layer is less than 25mm and the embedment depth is less than 15d. Seismic performance and fire resistance are both seriously deficient. The whole performance levels have been described in Table 2

Table2. Description of performance level and indices

Performance level	Performance index	
	Earthquake index	Fire index
Level 1	The angle of the steel beam under the peak load is less than 7θ, and the maximum rotation angle is greater than 14θ.	Fire resistance limit 2 hours, minor damage to the fire barrier
Level 2	The angle of rotation of steel beam is less than 7θ under peak load, and the maximum rotation angle is in the range of 10θ-14θ.	Fire resistance limit 1.5-2 hours, minor damage to the fire barrier
Level 3	The angle of rotation of steel beam is greater than 7θ under peak load, and the maximum rotation angle is in the range of 7θ-10θ.	Fire resistance limit 1-1.5 hours, moderate damage to the fire protection layer
Level 4	Destruction of the rear anchorage component immediately after loading	Fire resistance is less than 1 hour; fire protection layer is seriously damaged by fire

3. Conclusions

In this paper, numerical simulation has been carried out to investigate the seismic resistance and fire resistance of steel-to-concrete post-installed joint. The rotation angle of steel beam is selected as the critical index for seismic performance evaluation and fire resistance rating is used to assess the fire performance of post-installed connection. With reference to the definition of performance levels and performance indicators in current research results, four performance levels are defined, quantifiable performance indicators are given, and the values for both embedment depth and thickness of fire protection layer have been suggested for different performance levels. The performance-based methodology could provide guidance and technical support for the design of steel-to-concrete post-installed joint in the future.

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References
[1] Dongpo Wang , Dongsheng Wu , Siming He , Jun Zhou , Chaojun Ouyang, Behavior of post-installed large-diameter anchors in concrete foundations, Construction and Building Materials 95 (2015) 124–132,
[2] Dong Wang, Dondshengwu, Chaoyun Ouyang, Mingangzhai, Performance and design of post-installed large diameter anchors in concrete, Construction and Building Materials 114(2016) 142-150,
[3] Makoto Obata, Michio Inoue, Yoshiaki Goto, The failure mechanism and the pull-out strength of a bond-type anchor near a free edge, Mechanics of Materials 28 1998 113–12,
[4] Dongpo Wang, Dongsheng Wu, Siming He, Jun Zhou, Chaojun Ouyang, Behavior of post-installed large-diameter anchors in concrete foundations, Construction and Building Materials 95 (2015) 124–132,
[5] Sara Paganoni, Dina D'Ayala, Testing and design procedure for corner connections of masonry heritage buildings strengthened by metallic grouted anchors, Engineering Structures 70 (2014) 278–293,
[6] Bassam A. Tayeh, Zeyad M. EL dada, Samir Shihada, Moruf O. Yusuf, Pull-out behavior of post installed rebar connections using chemical adhesives and cement based binders, Engineering Sciences (2017),
[7] Philipp Mahrenholtz, Richard L. Wood, Rolf Eligehausen, Tara C. Hutchinson, Matthew S. Hoehler, Development and validation of European guidelines for seismic qualification of post-installed anchors, Engineering Structures 148 (2017) 497–508 ,
[8] Francisco González, Jaime Fernández, Galit Agranati, Paula Villanueva, Influence of construction conditions on strength of post installed bonded anchors, Construction and Building Materials 165 (2018) 272–283,
[9] Victor C.Li, Tetsushi Kanda, Engineered Cementitious Composites for structural applications.