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Multiple crack extension model of steel anchor bolts subjected to impact loading

Muhammad Saleem

Department of Mechanical and Energy Engineering, College of Engineering, Imam Abdulrahman Bin Faisal University, P.O. Box 1982, Dammam 31441, Eastern Province, Kingdom of Saudi Arabia

HIGHLIGHTS

- Micro-fractural force-deformation model with multiple cracks is presented.
- Model is capable to consider mechanical and material parameters of bolt-concrete.
- Model successfully predicts the load-deformation response of various bolts/fibers.
- Model is helpful for engineers/researchers to predict deformational response.

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ABSTRACT

Steel anchor bolts embedded in concrete are designed based on standards that assume to have a uniform stress along with single crack failure. However, experimental evidence has shown that the steel anchor bolt failure is governed by a combination of failure patterns such as cone and splitting type failure, hence the assumptions of uniform stress and single crack failure are not valid. In this regards the presented manuscript details an analytical model related to the anchor bolt failure subjected to impact loading. Impact loading is such that is introduced using a Schmidt Hammer in order to judge the pull-out strength steel bolts. The presented analytical model takes into consideration multiple crack extension scenarios, such as interfacial cracking initiated from top and bottom of steel bolt along with the case of simultaneous crack extension. The presented model is further capable of taking into consideration a variety of anchor types such as straight, hooked and bent type of anchors. The theoretical and experimental results comparison proved that the presented analytical model was capable of predicting the peak load capacity and could also simulate the pre and post peak failure mechanism. The proposed model can be employed by professionals to judge the deformational response of various types of steel anchor bolts.

1. Introduction

Much research efforts have been focused in the field of retrofitting and strengthening over the past few decades. Several new methods of strengthening have been invented along with rehabilitation techniques. In this regards steel anchor bolts are extensively used in the construction industry for a large variety of reasons such as for installation of temporary support structures to connecting structural elements together. The steel anchor bolts are under increased scrutiny with the resurgence of pre-fabricated structural elements and hybrid structures. Refs. [11,7] provided detailed guidelines for the design of post-installed anchoring systems by considering limit state design, fatigue and earthquake loading response. Refs. [22,8,20,9] also provided critical insight into the design and performance of headed, unheaded and grouted steel anchor bolts. Refs. [12,6,5] developed cracking pattern model for fibers embedded in the cementations material and conducted analysis of existing model for strengthening of concrete beams.

Although much research has been conducted in the field of steel anchor bolts however, very little attention has been paid to develop non-destructive testing techniques to evaluate the pull-out loading carrying capacity of anchor bolts. In this regards [13,14,15,16] developed a new non-destructive testing technique to estimate the pull-out load carrying capacity of steel anchor bolts by relating their pull-out strength to the Schmidt Hammer rebound number, [17] further refined the reliability of the non-destructive pull-out strength estimate by relating the bond quality of embedded steel bars to the ultra-sonic pulse velocity. As per ACI 349-13 [1] and ACI 318-14 [2] the anchor bolt failure mode can be categorized into four main classes such as a) Anchor bolt failure b)

E-mail addresses: mssharif@iau.edu.sa, c.engineer@hotmail.com

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Notations

A_A	area of anchor	q_{f1}, q_{f2}	frictional shear force per unit length on cracked interface
a_1, a_2	Interfacial crack length	q_{y1}, q_{y2}	maximum shear force per unit length
α	stress reduction ratio, q_f/q_y	r	radius of anchor bolt
D_A	diameter of anchor	Ω_f	work done by friction
E_A	elastic modulus of anchor	Γ	interface parameter
E_I	elastic modulus of interface	Ω_E	strain energy
k	shear stiffness of interface	ρ	perimeter of steel bolt
K_{END}	end spring constant	ζ_i	work of fracture at the interface
L	total length of steel anchor bolt	G	Energy release rate
L_D	anchor bolt embedment length	ψ	interface parameter
L_E	anchor bolt exposed length	R	Schmidt hammer rebound number
q_1, q_2	shear force per unit length on interface		

Concrete cone type failure c) Anchor bolt pull-out and d) splitting type failure. Cone type failure being the most common type has been investigated in detail by many researchers [21,4]. Ref. [3] developed a double-nodded zero-thickness interface element for 3D cracking propagation under mixed mode of failure.

From the through overview of the past literature it is evident that almost all the past research work has been focused on either the monotonic loading or the cyclic loading. Hence, in this regards the presented manuscript details the deformational response of steel anchor bolt subjected to cyclic loading. Furthermore, the multiple possibilities related to crack extension are taken into consideration. The factors effecting the steel anchor bolt pull-out load carrying capacity such as bolt diameter, its embedment length, alignment and the quality of concrete in the vicinity of bolt are also taken into consideration. Finally the deformational response predicted by the analytical model is compared to experimental evidence and a good agreement is found. The presented model can be employed by engineers and researchers to predict the peak deformational response of anchor bolts under variety of crack extension scenarios.

2. Materials and methods

2.1. Materials

Forty 150 × 150 × 150 mm concrete cube specimens as shown in the Fig. 1 along with six 150 × 300 mm cylindrical specimens for strength testing were casted, using OPC type-1 with a specific gravity of 3.15 in accordance with ASTM C150. The chemical composition of OPC by weight (%) was as follows: CaO = 64.3, SiO_2 = 22, Al_2O_3 = 5.64, Fe_2O_3 = 3.8, K_2O = 0.36, MgO = 2.11, Na_2O = 0.19 and equivalent alkalis ($Na_2O + 0.665K_2O$) = 0.42, loss on ignition was 0.7, C_3S = 55, C_2S = 19, C_3A = 10 and C_4AF = 7. Desert sand was used as fine aggregate possessing bulk specific gravity and water absorption of respectively, 2.66 and 0.60%. The water-cement ratio of 0.41 with water content was 120 kg/m^3; cement 290 kg/m^3, air entrainment 4.2%; sand and gravel 828 and 1043 kg/m^3, respectively. Limestone course aggregate with a maximum size of 19 mm was used and it was graded in accordance with ASTM C33, having a bulk specific gravity and water absorption of 2.45 and 2.05%, respectively. In addition, ASTM C33 conditions for coarse aggregate grading were satisfied by selecting sieve size 56 and aggregate size of 19 and 9.5 mm partitioned 85% and 15% by mass respectively. The slump was 100 ± 25 mm, curing was done in the temperature controlled water tank and the average 28 days compressive strength was 34.1 MPa.

2.2. Methods

Pre-construction installed steel anchor bolt with varying embedment length were investigated in the presented manuscript as shown in the Fig. 2. Each bolt had was made up of Stainless steel with a Rockwell hardness of B70 and a total length, L_T of 150 mm with 50 mm and 70 mm as embedment length, L_D and the remaining as exposed length, L_E. Each bolt was aligned in the middle of the pre-cast mold and was held in place with the help of guide wires. Five readings were taken on the top of embedded anchor bolt with the help of Schmidt hammer as shown in Fig. 2. The details related to preparing, casting, curing, experimental protocol, data collection and analysis are provided in earlier published work by the author (See [13,15,16] which deals with the development of non-destructive test method to evaluate the loading strength of steel bolts. The presented manuscript deals with the development of multi crack extension analytical model which is capable of predicting the pull-out load deformational response of various types of anchor bolts. In the past published work [13], the author measured the amount of impact energy imparted by the Schmidt hammer. It was found that the average impact energy imparted by the Schmidt hammer was 1.81 J. It is to be brought to the attention of the reader that since each anchor bolt is subjected to impact loading five times using Schmidt hammer, hence the combined effect of the imparted energy was taken into consideration in the presented manuscript.

It is to be brought to the attention of readers that impacting the top of the anchor bolt with the Schmidt hammer can cause interfacial bond damage for small anchor bolts. This aspect of the newly proposed non-destructive testing technique also shed light on the limitation, that the Schmidt hammer can only be used for small-to-medium sized anchor bolts. Furthermore, for large sized diameter anchor bolts the Schmidt hammer would not be able to impart sufficient amount of impact loading that can be used to effectively judge the quality of bond. Therefore, for anchor bolts used in the mining sector a modification to the impact loading mechanism would be required; in addition the cut-off diameter below which the Schmidt hammer impact loading would be effective is an area of further research and development.

However, from experimental data analysis published in the past research work it was found that since the Schmidt hammer imparts approximately 9 J of energy to the anchor bolt, the anchor bolts with good bond were successful in transferring the induced impact energy to the surrounding concrete resulting in a larger rebound number, R. However, the steel bolts with poor bond were not able to transmit the induced impact loading to the surrounding concrete resulting in lower rebound number, R. This phenomenon was used to identify steel anchor bolts with poor bond quality. In this regards the presented manuscript details the analytical model which is capable of taking into consideration the bolt alignment, its diameter, embedment length, concrete quality and micro-cracking at the concrete and bolt interface. The details of the model are provided in the proceeding section.

3. Analytical model description

Fig. 3 presents the conceptual details of the presented of the analytical model. The middle portion of the diagram details the anchor bolt embedded in concrete with expansion forces being generated as a reaction to the applied pull-out loading. The portion of the diagram on the right hand side details the mathematical description of the model where the interface between the concrete and steel bolt is modeled as shear-lag thus the interface deforms only in shear with a stiffness of k. Several types of steel anchor bolts are used in the practice, in this regards the end resistance used in the analytical model can be employed to estimate the end resistance provided by various types of anchor bolts such as hooked, straight and anchored bolts etc. In the presented manuscript the end condition of the anchor bolt is modeled as K_{END} as shown in Fig. 3. The steel anchor bolt is assumed to have a uniform constant cross-sectional area A_A, and is treated as a linear elastic with modulus of elasticity given as E_A while the surrounding concrete material is treated as rigid except the interfacial zone which is treated as non-linear. The poisons ratio is neglected since the