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Numerical simulations of progression of damage in concrete embedded chemical anchors

S. Sasmal[*1], R. Thiyagarajan[1a], K.H. Lieberum[2b] and E.A.B. Koenders[2c]

[1]*CSIR-Structural Engineering Research Centre, CSIR Campus, Taramani, Chennai-600113, India*
[2]*Institute of Construction and Building Materials, Technische Universität Darmstadt, Darmstadt, Germany*

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Abstract. In this paper, the performance of post-installed adhesive bonded anchor embedded in concrete is assessed using numerical simulations. This study aims at studying the influence of parameters on the performance of a chemically bonded anchorage system. Non-linear finite element modelling and simulations are carried out by properly using the material properties and phenomenon. Materials parameters such as characteristic length, fracture energy, damage criteria, tension retention and crack width of concrete and interface characteristics are carefully assigned so as to obtain a most realistic behaviour of the chemical anchor system. The peak strength of two different anchor systems obtained from present numerical studies is validated against experimental results. Furthermore, validated numerical models are used to study the load transferring mechanism and damage progression characteristics of various anchors systems where strength of concrete, strength of epoxy, and geometry and disposition of anchors are the parameters. The process of development of strain in concrete adjacent to the anchor and energy dissipated during the course of damage progression are analysed. Results show that the performance of the considered anchorage system is, though a combined effect of material and geometric parameters, but a clear distinction could be made on the parameters to achieve a desired performance based on strength, slip, strain development or dissipated energy. Inspite the increase in anchor capacity with increase in concrete strength, it brings some undesirable performance as well. Furthermore, the pullout capacity of the chemical anchor system increases with a decrease in disparity among the strength of concrete and epoxy.

Keywords: concrete damage; fracture energy; pull-out strength; chemically bonded; non-linear simulation; damage process; interface behaviour

1. Introduction

Recently, the world has witnessed the devastating effects, earthquakes have on structures and buildings (Elwood *et al*. 2016, Flint *et al*. 2016). Since, a large portion of the existing structures was old and deteriorated, those could not withstand the severe loading conditions for which they were not designed for. It is a standing challenge to the structural engineering community to retrofit the existing and deteriorated structures to a possible extent that makes them more earthquake resistant, as it is simply not feasible to declare the millions of structures as unfit. Retrofitting these structures has been one of the most commonly adopted methods to mitigate the destructive impacts of earthquakes. Many retrofitting schemes ranging from applications like concrete jacketing, steel plate jacketing, fiber reinforced plastics, fiber reinforced composites, engineered cement composites, prestressing, shape memory alloys etc., are being explored, investigated and attempted. Jacketing structural elements and integrating new shear walls into a structural system are the most preferred retrofitting methods for local and global retrofitting of deficient structures. The application of these retrofitting methods require anchors to connect new structural members to the system and to transfer the load between new and existing members. It is evident that the efficiency of the anchor system plays a vital role in dictating the performance of the retrofitted schemes and the behaviour of the entire retrofitted structure, as well.

Furthermore, it is envisaged to be appealing and extremely promising to develop retrofit schemes, which are structurally adequate, non-invasive and fast to install, since most of the reported techniques are exhaustively costly, difficult to implement and have a limited durability. Recent studies (Pampanin *et al*. 2006, Eligehausen *et al*. 2009, De Matteis *et al*. 2009, Sharbatdar *et al*. 2012, Sasmal and Nath 2016) showed that a steel bracing in the form of haunch could be an effective method to retrofit deficient structures. The non-invasive scheme as such is simple and straight forward (as shown in Fig. 1), but the force transfer mechanism needs to be ensured so that the force flows from beam to column through the bypass route of the haunch. During an earthquake loading, the anchorage system attached to both ends of the bracing (attached to beam and column, respectively) is of great importance, as it has to withstand the massive pull out force from the bracing.

Because of the easy installation procedure and easy

∗Corresponding author, Principal Scientist
E-mail: sasmalsap@gmail.com, saptarshi@serc.res.in
[a]Project Student
[b]Senior Scientist
[c]Professor

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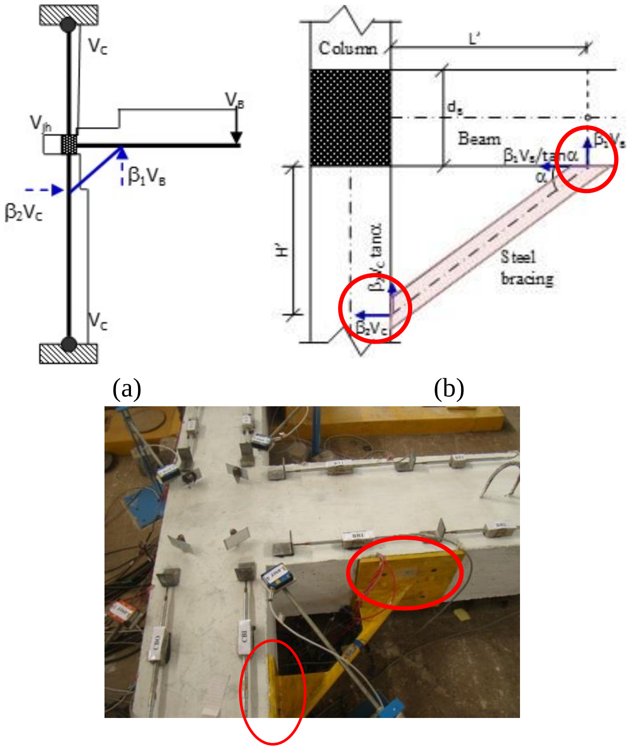


(a) (b)

(c)

Fig. 1 Structural arrangement (a) Re-distribution of force by adopting steel bracing, (b) force distribution at strut connection, (c) anchored retrofit scheme with RC structure

handling, post-installed chemical anchorages are the most preferred solution in seismic retrofitting of structures as they provide more flexibility at the application stage. Furthermore, cast-in end plate anchors are not suitable for retrofitting existing structures. To safely design such an anchor (embedded in concrete with adhesive interface), it is essential to have a thorough understanding on the behaviour of both the anchor in concrete and the factors that affect the capacity of anchor embedded in the concrete. Unlike cast-in anchors where the load transfer takes place through the head into the concrete, in adhesive anchors the load is transferred throughout the length of the shaft. This load transfer takes place as a result of three complementary mechanisms: adhesion, friction and keying effect of surfaces. The efficiency of an anchor depends on various parameters like embedment depth, adhesive quality, hole preparation, concrete grade, bore diameter, etc. Many concepts are being proposed to understand the complex force transfer of the chemical anchor system. It results from combined effects of geometrical- and material- properties of anchor, chemical interface and the embedded material. It is understood that the redistribution of forces along the anchor shaft is caused by the reaction from the movement of the particle in the concrete and that reaction is transferred to the anchor by means of shear resistance at the interfaces. Anchors chemically bonded to the concrete when subjected to tensile pull-out, based on the boundary and anchoring criteria, exhibits different failure mechanism such as bond failure, steel failure, concrete breakout and combined failure (Elegehausen *et al*. 2006).

Jalalifar (2006) brought out a very promising theoretical concept for describing and determining the load transfer mechanism in fully grouted anchor bolts. It is reported that there is only a weak chemical bond formation between the surfaces, implying that the major load transfer occurs due to the interlocking effect and the friction between the surfaces. Pull-out study of adhesive anchors has been a focus of study because of the wide variety of its application in the field of civil engineering. A number of experimental, analytical as well as numerical studies, has been made till date to understand the science behind the effective behaviour of adhesive anchors. Eligehausen *et al*. (2006) made both experimental and numerical investigations on the behaviour of adhesive anchors. They proposed a behavioural model for the design of adhesive anchors. Barnet *et al.* (2012), Bajer and Barnat (2012) made a characteristic and parametric study on the bond strength of glue-concrete and glue-anchor interface. Li and Bouzauli (2007) proposed a theoretical approach to study the interfacial shear stress between the anchor bonded into the concrete. The capacity dependency of anchors with adhesive quality was studied by Dudek and Kadela (2016). Colak (2001) focused his study on glue thickness and filler presence in glue over the capacity of bar embedded in precast panels. Jalalifar (2006) proposed a new approach to understand the load transferring between the concrete and the anchor bolt. Epakachi *et al.* (2015) conducted an experimental study on single anchor and anchor groups, which pointed out the scope for improvement in the provisions stipulated in ACI recommendation. The studies had been made on pullout behaviour of anchors in low strength concrete. Yilmaz *et al.* (2013) carried out numerous experiments on the anchor capacity of low strength concrete and they found that sufficient embedment depth and a free edge distance can counteract the negative effects of low strength of concrete over the anchor behaviour. The idea of partial bonding was proposed and studied by Gurbuz and IIki (2011), to compensate for a lower concrete strength. Similarly, a study on anchors in high performance concrete was carried out by Cattenea and Muciaccia (2015), where they proposed an approach to predict the tensile capacity of anchor in high strength and ordinary strength concrete. The embedment depth, as a parameter for anchor capacity, was studied by Delhomme *et al*. (2015, 2016) and the failure mode with the variation in embedment depth were reported. Xu *et al.* (2011) numerically studied the anchor capacity with embedment depth and their corresponding crack patterns. Eligehausen and Appl (2007) numerically investigated the performance of the anchor system and proposed behavioural model based on a uniform bond stress model to predict the capacity of single and group anchors. Kim *et al.* (2007) numerically simulated the load transfer mechanism of an adhesive ground anchor and prescribed a methodology to achieve results that are more realistic. Yang *et al.* (2007), Wu *et al.* (2007) defined a new theoretical approach with two different boundary conditions to understand the pullout of anchor conditions wherein they studied the shear stress distribution within the adhesive thickness. It is found that most theoretical formulations to predict the capacity of anchors are based on interfacial debonding and crack propogation of tensile cracks. Tang (2015) established a relation between the concrete strength and bond strength and reported dependency of bond strength over the rib to anchor diameter ratio. A series of experimental and analytical studies were made by Rizzo *et al*. (2010), Spada *et al.* (2011) to understand the elasto-plastic behaviour of anchor subjected to pullout. They proposed a simplified model to predict the pullout, which overcomes the major limitations of existing analytical models. Li *et al.* (2013) carried out the numerical investigations to understand the load transfer mechanism at the anchor ribs and the pressure distribution along the embedded length of anchoring. Kabir and Islam (2014) numerically analysed the stress distribution along the length of the anchor and found out the critical zone that is prone to cracking.

Though a considerable amount of investigations is already reported, the existing knowledge for designing a chemical anchor system, embedded in concrete, especially for newly developed concretes with advanced properties, can still be improved. Most of the research works are concentrated towards developing models to evaluate the strength of the anchor system, which is not sufficient for designing the same for structural system. Design of anchor systems should contain the entire performance of a system encompassing the failure mechanism, crack formation, strain distribution and load-slip characteristics. A complete understanding of the behaviour of anchor systems would facilitate a better retrofit strategy towards performance based retrofit/rehabilitation of structures. As discussed in the preceding sections, a chemical anchor system is quite complex with multi-material interfaces (contact) and varied failure mechanisms depending on the strength, fracture energy, damage criteria, tension softening and other non-linear properties. Numerical investigations using experimentally validated 3 dimensional simulation model would be of great importance to carry out a detailed study and to provide the closer look at how various parameters of a chemical anchor system are interactively contributing to the load transferring mechanism. Present study is focussing on categorically addressing the influence of geometry, configuration and material properties of the anchor system on the progression, strain development and finally the pull out capacity.

2. Numerical modelling and simulations

In present study, the nonlinear finite element based analysis platform ATENA (3D V5) is used, which is very powerful in capturing damage in concrete like brittle materials. To understand the assumptions and applicability of ATENA for non- linear analysis of concrete anchorage system, a brief discussion on the key issues concerning the material models and their behaviour is presented here.

Material model for concrete

Concrete is considered to be a quasi-brittle material which, whenever subjected to tension and compression, undergoes cracking and crushing. It possesses a nonlinear nature in compression, and in tension it undergoes a linear stress-strain response up to its tensile limit resulting in cracking followed by an abrupt loss in strength. The cracking response can be modelled by discrete- or smeared-crack model. In a discrete cracking model, it is needed to model each and every crack. Due to the controllable computation demands, smeared approaches are adopted in almost all FEM packages. The concrete model in ATENA combines constitutive models for tensile and compressive behaviour. The smeared crack approach is used to model the crack properties so that the material properties defined are valid within the whole material volume. The material model for concrete in ATENA is capable of capturing the following features: i) non-linear behaviour of concrete in compression including hardening and softening, ii) fracture of concrete in tension based on non-linear fracture mechanics, iii) biaxial strength failure criterion, iv) reduction of compressive strength after cracking, v) tension stiffening effect, vi) reduction in shear stiffness after cracking, and vii) crack direction based on the adopted fixed or rotating crack model. In the present study, the concrete model “CC3DNonlinearcementitious” is used with the model for concrete fracture and concrete plasticity behaviour as proposed by Menetary and Willam (1995). In the fixed crack model (Rots and Blaauwendraad 1989), the orientation of the crack is constant during the entire computational process whereas in the rotating crack model the crack direction may change with the load history. Therefore, a fixed crack model is more computationally intensive than a rotating crack model. The fracture model is based on a smeared crack approach and on a crack band model. It employs Rankine failure criteria, which assumes that strains and stresses are converted into the material directions, which in case of a rotating crack model, corresponds to the principal directions. In case of a fixed crack model, those are given by the principal directions at the onset of cracking.

The tension stiffening, which defines the relative limiting value of the tensile strength of concrete, was considered as 0.4 (Sasmal *et al*. 2011). The tensile softening is a function of the crack opening and is based on Hordijik’s formula (1991). It proposes that the crack opening can be calculated from fracturing strain ε'^{f}_{kk} in Z direction plus the current increment of fracture strain $\Delta\lambda$ and the sum is multiplied by the characteristic length L_t, a concept introduced by Bazant and Oh (1983). In ATENA, the characteristic length or crack band size is calculated as a size of the element projection in the crack direction. Remmel (1994) presented an approach to calculate fracture energy as G_f=65.*ln* (1+f_c/10) N/m where the compressive strength of concrete and particle size are the parameters. Here, the empirical factor was taken as 65, and size of aggregates is considered as16 mm. Results obtained from a series of experiments are compared with the equation along with the equation proposed in CEB-FIP model code 90. It was pointed out that there is a good agreement among the results obtained from the test and the value as proposed by Remmel whereas values obtained from CED-FIP model code 90 are 25% less than that obtained from the tests. In present study, the fracture energy is calculated as proposed by Remmel where G_f and f_c are facture energy of concrete and compressive strength of concrete cylinder, respectively.

Material model for Epoxy and anchor

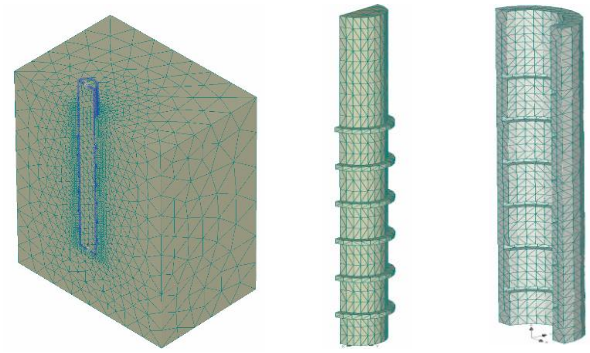
The adhesion is modelled as user defined cementitious model “CC3Dnonlinear cementitious model” which enables a user defined stress strain law, tensile compressive behaviour, shear retention factor and effect of lateral compression on tensile strength. The elastic modulus of the adhesive is kept constant at 3500 N/mm^2 and the Poisson ratio is defined as 0.3. The anchor material is defined as “3D elastic isotropic” with the Young’s modulus of the anchor as 2×10^5 MPa and the Poisson ratio of 0.3. This material model considers a linear behaviour of steel within the elastic limit. Since, both the adjacent material such as epoxy and concrete has a much lower strength and stiffness, it is envisaged that the nonlinear strain hardening of the steel anchor will not be activated throughout the loading state of the anchor system.

Interface model

Debonding at the interface is generally a function of bond strength characteristics between the two surfaces in contact. In this case, it is between the anchor-epoxy and epoxy-concrete interfaces. Contact between concrete and epoxy is most critical since the load transfer of an anchor mainly relies on the interfacial strength of concrete-epoxy and since modelling of the interface is not straight forward as well. In ATENA, there are two methods to define an interface, viz., perfect connection and interfacial elements between the two surfaces in contact. The parameters that define the interfacial behaviour are friction coefficient, stiffness, tensile strength of interface and cohesion between the two surfaces in contact. The interface description in ATENA includes two sets of stiffnesses in each direction (normal and tangential stiffness) where the normal stiffness is valid until reaching the ultimate stress value at the contact and tangential is after reaching the same (ATENA Theory Manual 2006). The normal and tangential stiffness can be approximated by dividing the minimal elastic modulus and shear modulus of surrounding material with the thickness of interface. An interface connection is used in this study with appropriate material properties. This approach relies heavily on the accuracy of constitutive model for the concrete material and the size of mesh element beneath the adhesive layer. Hence, a much finer meshing is needed beneath the interface to accurately imply the node to node load transfer in the model.

Geometric modelling

The total anchorage system is divided into 3 distinct layers as anchor, adhesive and concrete, with each layer being a separate macro element. Half the anchorage system, with proper symmetric boundary conditions, is modelled to reduce computational time required for the analysis. It is to mention that the results (total pull out forces) are accordingly corrected for the full global model. The model corresponding to the half symmetry is shown in Fig. 2. For the first validation with experimental studies from Gurbuz and IIki (2011), the total embedment depth of the anchor is considered as 127 mm and it is embedded in a concrete slab. The clear spacing between the top of the embedment and the first rib is 27 mm. The anchor is restrained at the bottom against vertical movement as well as rotation. The concrete is arrested in all its faces perpendicular to the direction of face. The boundary conditions are given such that the model represents the experimental pull-out setup where the anchor is surrounded by concrete. The two top edges of the concrete are arrested vertically which represent the reaction frame of the experimental setup. A constant pull-out displacement is applied at each step and the corresponding reaction is noted down. In all the layers, the tetrahedral micro-elements are defined. After a detailed convergence study, it was decided to use a mesh size of 5 mm along the anchor and 2 mm along the epoxy such that the mesh at the vicinity of the two interfaces is sufficiently refined to predict the reliable result. Since in ATENA, the load transfer is through node-to-node interaction of finite element, it is very important to check the compatibility of the mesh, specifically at the interface. The macro elements are created with a geometry in such a way that the compatibility condition for mesh at and around the adhesive is attained (shown in Fig. 2(a)). Figs. 2(b) and 2(c) show the anchor macro elements and adhesive used in the study. These two elements are created as a lock and key, so that the anchor exactly fits into the adhesive layer. The interfacial behaviour of epoxy concrete and epoxy anchor are simulated by defining it as a perfect connection. The interfacial material is based on Mohr- Coulomb criterion with tension cut-off. Bond between the concrete and epoxy is subjected to both tensile as well as shear forces. It was found that during experiments bond failure started in the form of tensile failure in concrete beneath the interface. The normal stiffness comes into act before the bond failure whereas the tangential stiffness is a post peak stiffness, which is used only in numerical studies to maintain the positive definiteness of solver equations. Theoretically, the post peak stiffness is zero, which might lead to indefinite stiffness of the global system. Hence, the tangential stiffness is given at least 1000 to 10000 times less than the normal stiffness.



(a) (b) (c)

Fig. 2 Numerical model of the chemical anchor embedded in concrete, (a) Half symmetric model of the anchor system, (b) Ribbed anchor, and (c) Adhesive interface layer between anchor and concrete

3. Solution strategies and validation

Newton-Raphson method of iteration was implemented

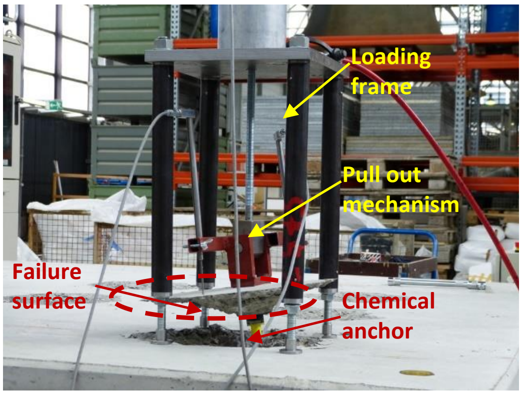


Fig. 3 Experimental set up used for carrying out the pull-out tests on chemical anchors embedded in the concrete

using the displacement control to obtain numerical solutions. The size of each load step was found to have significant impact over the final observation. Hence, an optimum load step size of 0.005 mm is used in this study. To validate the numerical model developed to simulate the pull out behaviour of the chemical anchor system, two reported experimental studies from two very established research groups are considered. First is, as mentioned previously, with Gurbuz and IIki (2011) and second was with the investigations carried out at Technische Universitaet Darmstadt, Germany (shown in Fig. 3).

The two experimental studies are chosen in such a way that the efficiency of the developed numerical models can be assessed on different anchor diameters, embedment length and strength of concrete, which can provide the required confidence on the accuracy of the developed numerical models. Table 1 shows the comparison of results obtained from the numerical simulations with those reported from the experimental studies. The results show that the developed numerical model is reasonably sound in predicting the experimental results. After the validation studies, detailed investigations are carried out to understand the influence of various parameters that are dictating the damage process in- and developing the pull out strength of- the anchor system.

4. Results and discussion

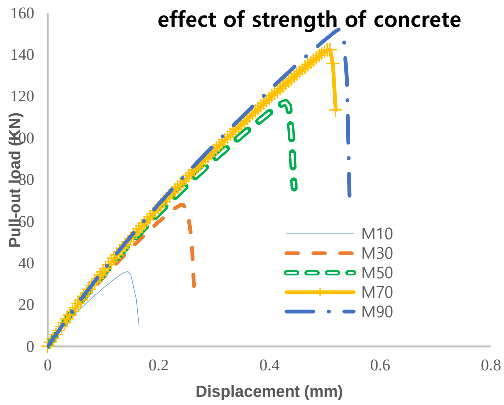
The validated numerical model is used for extensive simulation studies to understand the influence of various geometric and material parameters on the progression of damage in the concrete region and to evaluate the overall response of the chemical anchor system. The role of concrete compressive strength, epoxy quality, anchor geometry on the crack formation, strain development, ultimate pull-out strength and energy dissipation capacity of the adhesive bonded anchor is investigated in the present study.

4.1 Pullout-slip displacement behaviour

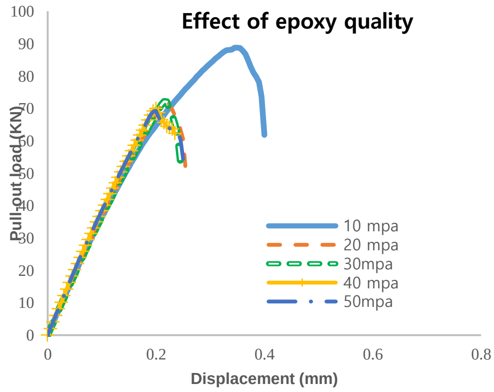
It may be evident that strength of concrete and epoxy, and the geometry (size and pitch) of the anchor ribs are the key parameters, which dictate the pullout-slip behaviour of the chemical anchor system. To represent both old and newly designed concretes, wide ranges of concrete compressive strength from 10 MPa to 90 MPa are considered in the present study. Furthermore, the tensile

Table 1 Validation of the results obtained from present study with reported experimental studies

Author	Concrete strength (MPa)	Embedment length (mm)	Anchor size (mm)	Pull-out load (KN): Reported Experimental studies	Pull-out load (KN): Present numerical studies (% deviation)
Validation 1 Gurbuz and IIki (2011)	12.7	96	16	44.5	41.28 (6.8%)
	Specific fracture energy=32.66×10^{-6} MN/m, Critical compressive displacement=0.5 mm, Plastic strain at compressive strength=5.22×10^{-4}, Reduction of compressive strength due to crack=0.8, Failure surface eccentricity=0.52				
Validation 2 University of Darmstadt (2008)	33.8	127	16	78.5	75.58 (3.72%)
	Specific fracture energy=62.72×10^{-6} MN/m, Critical compressive displacement=0.5 mm, Plastic strain at compressive strength=9.02×10^{-4}, Reduction of compressive strength due to crack=0.8, Failure surface eccentricity=0.52				



(a)



(b)

Fig. 4 Pull-out slip behaviour of different anchor system, (a) varying strength of concrete (M10 stands for concrete mix with 10 MPa), (b) varying strength of epoxy

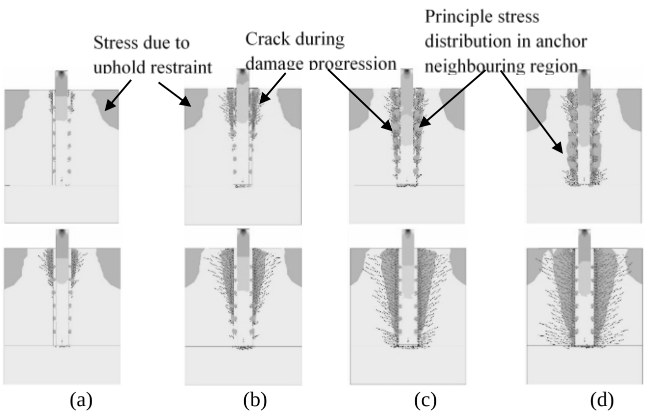


Fig. 5 Crack progression in the anchor system with compatible strength of epoxy and concrete (top) and high strength concrete (bottom) ((a) to (d) shows the crack and stress profile during 25%, 50%, 75% and 100% of the pull-out strength, respectively)

strength of epoxy is varied from 10 to 50 MPa. The pullout-slip behaviour of the anchor system is shown in Fig. 4(a) and (b) where the compressive strength of concrete and tensile strength of epoxy are the parameters. It becomes clear from Fig. 4(a) that as the strength of concrete increases, the pullout strength also increases, but the rate of increase significantly reduces when the strength of concrete exceeds 50 MPa, due to the increase in the brittleness of high strength concrete. In each case, failure is caused by a concrete cone breakout, which is characterised by the tensile cracks radiating from bottom of the anchor depth. Since, the stiffness of the system does not change considerably with change in concrete strength, higher pull-out strength from a higher concrete strength is achieved through larger slip. Pull-out strength of 50 MPa and 90 MPa concrete is 220% and 316% higher than that of system with 10 MPa concrete. Similarly, slip corresponding to pull-out strength of 50 MPa and 90 MPa concrete is 196% and 250% higher than that of system with 10 MPa concrete.

The effect of adhesive quality on the pull out-slip behaviour is depicted in Fig. 4(b). It is interesting to note that the pull out strength is almost similar for all cases of epoxy strength except the one with 10 MPa tensile strength. During pull out, three weak zones in the chemical anchor system are critical, i.e., steel-epoxy interface, epoxy layer and concrete-epoxy interface. The results point out that the pullout strength can be maximised when the strength of epoxy is similar to that of the bond strength of the concrete-epoxy interface (8 to 12 MPa). Therefore, the ultimate load carrying capacity of a chemical anchor is primarily dictated by the bond strength, which is the peak value of shear stress on the interfaces.

From the study, it is evident that the tensile cracks start propagating from the epoxy-concrete interface, but the characteristics of the crack propagation in case of the compatible epoxy strength and high concrete strength is quite different. Fig. 5 shows the crack initiation and propagation with principle stress development in the aforementioned anchor systems. It is interesting to note that the crack development in the compatible epoxy system

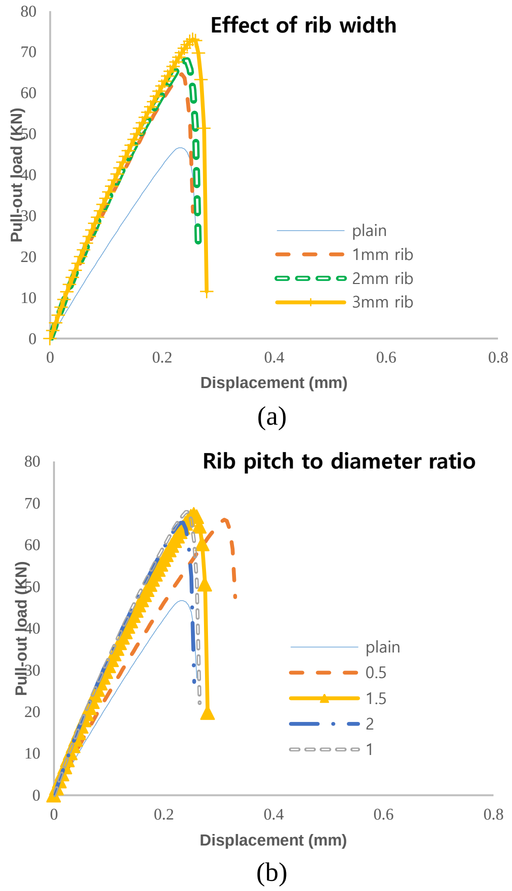


Fig. 6 Pull-out slip behaviour of anchor system with different anchor geometry, (a) varying rib diameter, (b) varying rib pitch

occurs in the anchor-epoxy interface and propagates through the epoxy layer, and transfers to the concrete (Fig. 5 (a) and (b), top). During the pull out process, crack formation and stress distribution along the depth of the anchor is quite uniform and ribs of the anchor play an important role in force transfer mechanism (Fig. 5 (c) and (d), top). In the anchor system with high strength concrete (a typical case with concrete compressive strength of 90 MPa), the phenomenon is quite different. Crack initiation takes place in the epoxy-concrete interface and propagates through the concrete (Fig. 5 (a) and (b), bottom). Eventually, the anchor ribs could not play the significant role and the anchor with epoxy acts as the single system against the concrete at the interface. It may also be important to mention that here the stress distribution in the neighbouring region of anchor, as in later case, are not as uniformly distributed as in the former case, where the stress distribution is wide (Fig. 5 (c) and (d), bottom) and capable of mobilising greater volume of material.

Influence of geometry, namely rib size and pitch, on the pullout-slip behaviour is shown in Fig. 6(a) and (b). The load transfer of the adhesive anchor is the combined work of interfacial friction between the two interfaces (anchor-epoxy and epoxy-concrete) and the interlocking effect of ribs. Fig. 6(a) depicts the influence of rib width over the pull-out capacity of concrete. When the rib area increases,

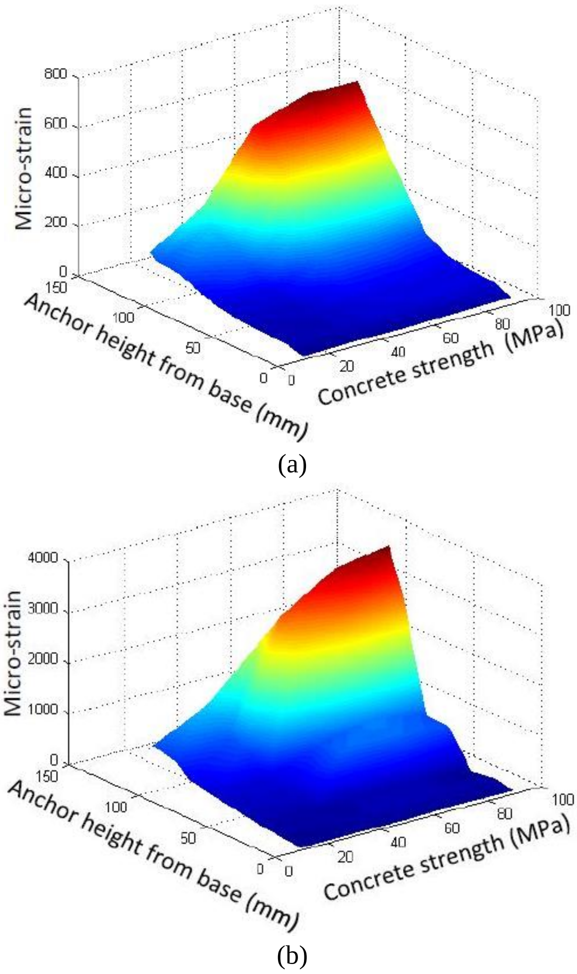


Fig. 7 Distribution of strain along the depth of anchor with different concrete strength, (a) at 25% of respective peak load, (b) at 75% of respective peak load

the pull-out strength marginally increases. For example, 1 mm rib offers almost 40% more pull-out strength and 51% stiffness than that of plain anchor, whereas, 3 times increase in rib diameter can only increase only about 12% of the pull-out strength and no improvement in stiffness with respect to the anchor with 1 mm rib. Therefore, it is significant to note that the increase in rib width cannot notably change either the stiffness or the strength of the system. Fig. 6(b) shows the influence of the pitch of the rib on the pull-out strength of the adhesive anchor. It is observed that when the ribs are close (pitch is low), there is additional slip and the system is less stiff than that observed from other cases. When the number of ribs is relatively less (larger pitch), then the system becomes stiffer (26% increase in stiffness with pitch ratio of 0.5 to 1.0). It reflects the better force transfer mechanism in anchor system with a larger pitch. This can be explained from the fact that when the ribs are too close, not enough epoxy will be available between the ribs to transfer the shear force (absence of locking mechanism) to the concrete interface. It is also observed that when the pitch to diameter ratio is more than 1, the pull-out strength does not vary with the pitch of the ribs. This supports the fact that the load transfer is predominantly due the friction and micro-keying at the

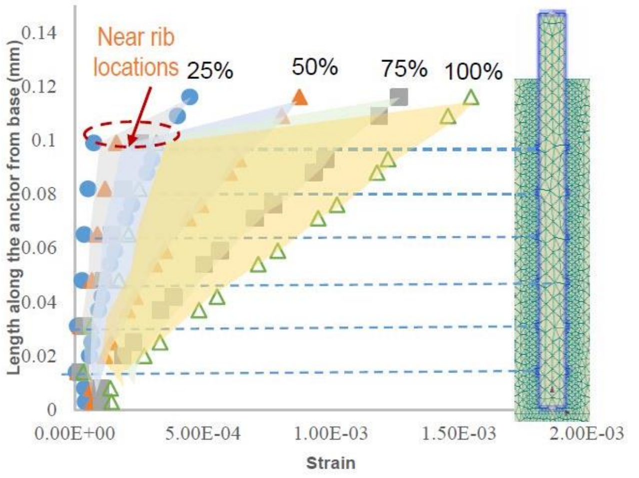


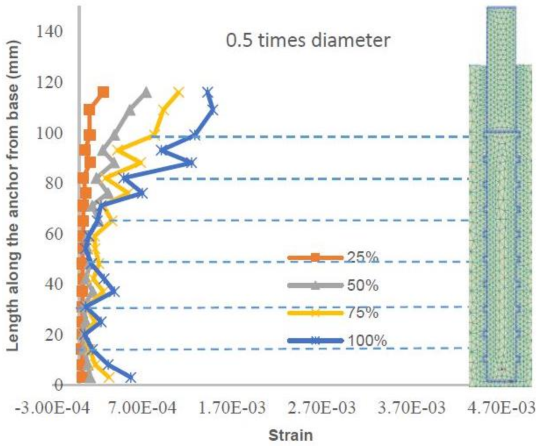
Fig. 8 Difference in distribution in strain in rib region and neighbouring region at different stages of damage

interface and not significantly through the interlocking of ribs with epoxy.

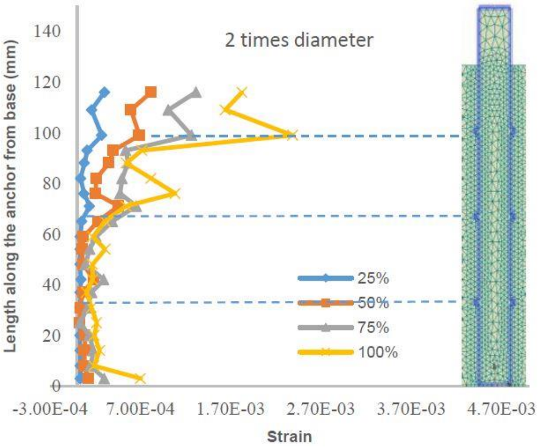
4.2 Strain development during pull out event

In addition to the studies on pull out load -slip displacement behaviour and crack formation of the chemical anchors, it is significant to study the development of concrete strain that is surrounding the anchor. It will enable to link the progression of damage of different types of anchor systems. The strain profile along the length of the anchor embedded in concrete of different strengths is shown in Fig. 7. For ease of understanding, the strain profile only at the stage of 25% and 75% of pull-out strength of the corresponding anchor system is depicted in Fig. 7(a) and (b), respectively. The figure reveals that (i) characteristics of strain distribution at different stages of damage in anchor systems does not alter significantly. (ii) Predominant strain development takes place in the top portion of the anchorage length and the length increases with the increase of the concrete strength. (iii) Due to high tensile strength and large fracture energy of high strength concrete, strain carrying capacity is much more than that observed for other systems with a low/normal strength concrete. (iv) The magnitude of strain in the anchor system for a low and high strength concrete near to the peak pull-out load is significantly different, which underscores that the failure mechanism is very different for anchor systems with low and high strength concrete.

The strain profiles of anchor systems with different rib size are studied at different stages of damage (25% to 100% of pull-out strength) and a typical result for anchor system with 1 mm rib is shown in Fig. 8. It is clear that the strain along the concrete increases from bottom to top in the anchor, which is in accordance with the elastic bond theory that stated that the maximum bond stress occurs at the top part of anchorage depth and decreases along the depth of the anchor. It may be important to note that for all cases, the concrete strain, at points corresponding to the rib, experiences a sudden dip and the points just above the rib level have more strain. Fig. 8 exhibits that at all stages of



(a)



(b)

Fig. 9 Strain profile of anchor systems with pitch to diameter ratio: (a) 0.5, and (b) 2

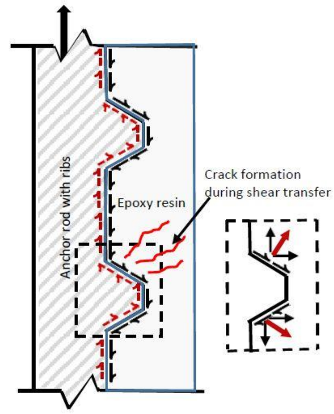


Fig. 10 Force transfer through the ribbed anchor to concrete through the epoxy region

damage, the concrete strain near the rib is much less than that at locations further away from the rib. For example, in an anchor system with a 1 mm rib, the strain drop near the rib is almost 70-80% of that further away from that region. It is also found that the difference of strain variation near to a rib of the neighbouring region increases with increase in damage in the system. Uneven strain distribution in concrete like homogeneous brittle material expedites a process of damage.

Strain profile in the anchor system with two distinct pitches (i.e., 0.5 times and 2.0 times of the diameter of the anchor) at various stages of damage is shown in Fig. 9. As already discussed, both anchor systems exhibit similar pull-out strength (can also be found in Fig. 6), though the strain distribution in concrete is interestingly very much different. For instance, at 50% of the peak pull-out load, the maximum strain in the anchor system with a pitch of 2 times diameter is 15% more than that observed from the anchor system with a pitch of 0.5 times the diameter, which increases to almost 70% at the stage of peak load. It underscores that, for the anchor system with almost similar strength, the force transfer mechanism from steel anchor- to epoxy interface- to the base concrete- is different when the pitch or size of the anchor changes. From the behaviour, it can be stated that once the chemical bonds are broken, the relative displacement between the two surfaces develop friction, which implicitly determines the force transfer mechanism. The inclined rib geometry is subjected to a normal force, which turns into a reaction acting on the adhesive resin. Once shear failure occurs at the anchor-adhesive interface, the rib surface is subjected to a mechanical interlock with the epoxy, which in-turn produces a shear force over surface of the rib (shown in Fig. 10).

Hence, it needs further investigation to understand the behaviour of rib geometry of chemical anchor systems on the strain distribution and progress of damage. Fig. 11 shows the effect of each rib size at a particular load. From Fig. 11, it can be observed that the geometry of the rib has significant effect on the strain in concrete. The localised distribution of compression and tension zones around the rib provides a clear idea on the variation in strain in the anchor system, for different types of rib geometry. A closure look would help in describing the phenomenon from a mechanics point of view. For a 1 mm rib, the compression- and tension- zones are confined to a smaller area inside the epoxy layer and hence, the radial stress is uniformly distributed into the interface. Hence, the strain profile along the anchor depth is smoothly distributed (ref to Fig. 9). For 2 mm and 3 mm ribs, the compression zone is dominated over the tension zone (can be seen from Fig. 11) that occurs due to the chemical bond between the two surfaces. When the ribs are of larger size, the space inside the epoxy layer to distribute the stress into the interface is less and hence, there occurs overlapping (super imposition) of radial stress radiating from the ribs.

4.3 Energy dissipation during pull-out event

Along with the strength, crack propagation and strain studies, it is important to investigate the efficiency of the anchor system in terms of energy dissipation, that happens during the pull-out event of the anchor. It is extremely significant since in the event of an earthquake or other dynamic impact load, the energy dissipation capacity of the system dictates the performance of the it. Fig. 12 depicts the energy dissipation of anchor systems with different variables. Energy dissipation in anchorage is the

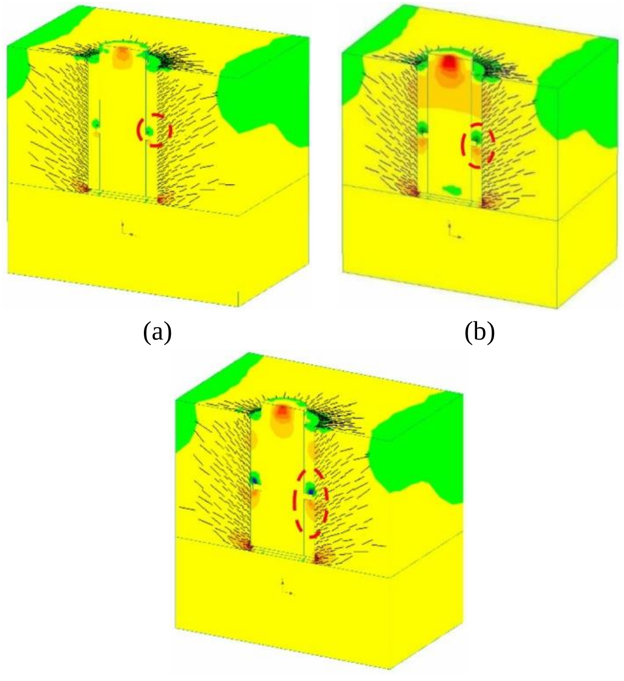


Fig. 11 Development of strain in micro zones around the anchor of different rib sizes (a) 1mm (b) 2mm (c) 3mm

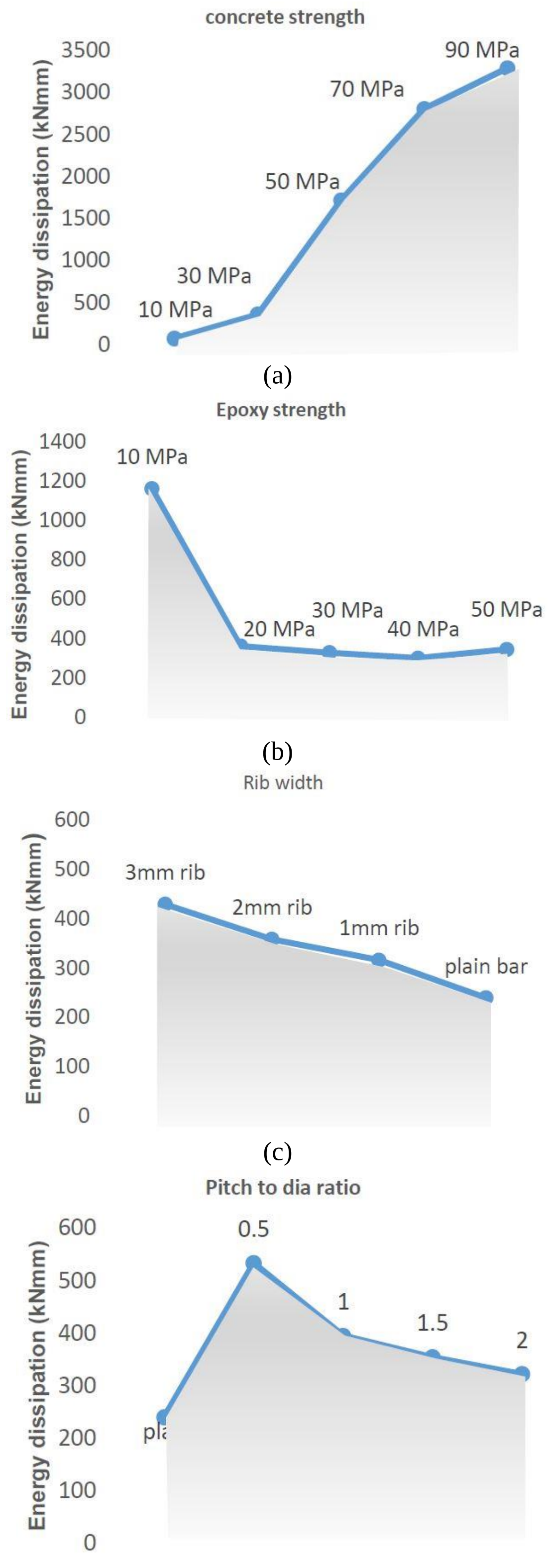


Fig. 12 Dissipation of energy with different parameters (a) concrete strength (b) epoxy strength (c) rib width (d) pitch to rib ratio

transformation of static energy (potential energy of system) into kinetic energy (friction and interlocking). It is to note (Fig. 12(a)) that the potential energy of a system increases as its compressive strength increases, although the degree of energy dissipation starts is reduced for higher strength concretes. Fig 12(b) shows the energy dissipation of an anchor system embedded in a 30 MPa concrete with different epoxy tensile strengths. It is clear that the energy dissipation reduces as the tensile strength of epoxy increases. This is because of the fact that the transfer of energy is subjected to little resistance when the system is nonhomogeneous. Hence, more energy is dissipated when the system approaches homogeneity (tensile strength of epoxy approaches towards the tensile strength of concrete). Energy dissipation is monotonically increasing with increasing rib area (Fig. 12(c)). This is because anchors with larger ribs may not be able to provide a significant increase in pull-out strength, but instead, the mobilization of material to form the long cracks and better interlocking mechanism from anchor with larger ribs provides a better energy dissipation. Fig 12(d) shows the variation of energy dissipation with a different pitch to diameter ratio. It is clear that anchors with a pitch of 0.5 times the diameter appears to have the maximum energy dissipation while the energy dissipation decreases as the number of ribs decreases. It provides important information on appropriate (performance based design) design and application of anchor for seismic resistant structures.

5. Conclusions

An improved understanding of the working principle and hierarchy of parameters are needed for an efficient design of adhesive anchors. In this study, the performance of adhesive anchors, embedded in concrete are evaluated, and the influence of various parameters were studied numerically. It is found that using the nonlinear finite element analysis with proper material parameters and analysis protocol, the performance of in concrete embedded chemical anchor systems can be determined with a reasonable accuracy (about 10% deviation). Displacement controlled mode (during loading) with very fine steps is advisable (based on affordable computational cost) to determine near accurate results and to capture the step by step damage propagation in the anchor system. It is identified that fracture energy, tension retention, and interface stiffness(es) are the most crucial parameters for appropriately simulating the concrete non-linearity and the same has to be arrived after meticulous studies. During numerical simulations, it is found that the very fine element modelling of ribbed bars with proper contacts with adjacent epoxy are essential to establish the mechanical gripping phenomenon taken place during the pull out of the anchors. Further, the present study shows that strength of concrete does not linearly influence the performance of the anchor. However, there is a synergy between the strength of concrete and geometry of the anchor. The present study brings out that for a given anchor (geometry) with given embedment depth, the capacity of the anchor starts shading away when concrete strength reaches a threshold value and the anchor performance increases tremendously when the strength of the adhesive is relatively close to the tensile strength of concrete. The load transfer is mainly due to the interfacial parameters (friction and micro keying) and the rib is very much dominating only in preventing the slippage and it is at maximum near the free end of the anchor and it decreases along the depth. In the present study, the load transferring mechanism of ribs is clearly simulated. Higher rib area results in improved and wider load transfer, however, the difference is not so significant. Energy dissipation capacity of any anchor system is found to be a good indicator for checking the adequacy of the system for the seismic resistance structures. The present study paves the way for a performance based design of anchor systems, which needs to be used for newly developed but not fully explored concrete such as high ductile, strain hardened or low carbon concrete. The present study also indicates on the possibility of developing new cement based binding material (engineered cement composite) for designing effective and durable anchor systems.

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