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Multi-layer model for pull-out behavior of post-installed anchor

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ABSTRACT: The effect of the interface properties such as stiffness and the strength on the pull-out behavior of a post-installed anchor bar is investigated using a multi-layer analytical model in this study. The anchor bar is such that used in the concrete jacketing method to strengthen reinforced concrete bridge piers. The mechanical properties of the infill layer are different from the surrounding concrete. Therefore the existing pull-out model of deformed bars cannot be applied directly in this case. By the sensitivity analysis the effect of these parameters is clarified on the load-displacement curve, shear stress distribution, de-bonded length and the damage of the surrounding concrete. Then the optimum combination of these parameters is investigated. From the above analysis, it is confirmed that the elastic modulus of the interface should be large to reduce the pull-out displacement and the increase of the shear strength of the interface makes the pull-out load larger.

1 INTRODUCTION

Earthquakes are a very common phenomenon throughout the world and strengthening techniques are often employed to either rehabilitate an already damaged structure or to further strengthen a structure against any impending damage. Many techniques are employed for this activity, among them one of the most common technique is that of concrete jacketing. Concrete jacketing technique is most commonly employed for its low cost and wide applicability. In this paper the influence of the infilled material properties on the deformational behavior of the retrofitted structure has been investigated.

The influence of the interface properties such as the stiffness and strength on the pull-out behavior of the steel reinforcement anchor bar embedded in concrete is investigated using a multi-layer analytical model in this study. The anchor bar in the concrete jacketing method is covered with epoxy resin layer the mechanical properties of which are different from the surrounding concrete. Therefore the existing pullout model of deformed steel bars cannot be applied directly. The bond between the steel reinforcement anchor bar and the infilled material is examined using the strength criterion approach.

The desirable interface properties are the ones which lead to the smaller displacements at the maximum pull-out load causing a reduced residual displacements and less damage to the surrounding footing, which makes the repair work easy and reduces the cost (Tsubaki & Wabiko 2008). The interface between the steel reinforcement and the surrounding concrete is modeled as a multi-layer zone. The mechanical properties of each layer are to be optimized so as to minimize the residual displacement and the damage in concrete of the footing in actual construction application. Previous work has shown that these properties have a considerable effect on the overall pull-out behavior of the post-installed anchor bar and are effective in achieving the optimum solution (Tsubaki & Saleem 2009).

The analytical model presented here consists of an anchor bar connected to the bottom end spring, surrounded by the multi-layer interface zone representing the infilled material such as epoxy resin. Two pre-existing cracks of varying lengths are assumed at the top of each layer. De-bonding is assumed to initiate at the top of the anchor bar. The bond stress at the de-bonded zone is kept as the reduced value of the bond strength considering the bond condition of the de-bonded zone. In the bonded zone the interface layer is kept in the elastic condition. The relationship between the pull-out force and pull-out displacement together with the influence of the material properties of the interface zone on the pull-out behavior is obtained from the analytical model.

Finally the influence of the elastic modulus and the strength of the interface on the pull-out behavior is investigated, how the elastic modulus of the interface work to make the pull-out displacement small, how the strength of the interface should be to make the maximum pull-out force large. Then the optimum combination of these parameters is investigated. The optimum condition is defined as the condition for the post-installed anchor which leads to larger pull-out force and smaller damage to the surrounding material. This condition is considered necessary for small residual displacement of a bridge pier and small damage zone in a footing.

2 ANALYTICAL PULL-OUT MODEL

2.1 *Modeling*

The pull-out behavior of an anchor bar from the surrounding concrete is modeled by the shear-lag model using the strength criterion (Tsubaki & Sumitro, 1998a,b, Stang & Shah 1990) as shown in Figure 1. The analytical model consists of an anchor bar connected at the bottom end spring representing the effect of geometrical constraint of the anchor bar, surrounded by the multi-layer interface zone representing the infilled material such as epoxy resin.

The continuity between the first, internal interface layer and the second, external one is assumed at the interface between the two layers. The second interface is connected to the surrounding concrete. The constitutive relationship of interface is assumed to be elastic up to the yield point and then the stress is kept constant depending on the reduction factor. The surrounding concrete is assumed to be rigid.

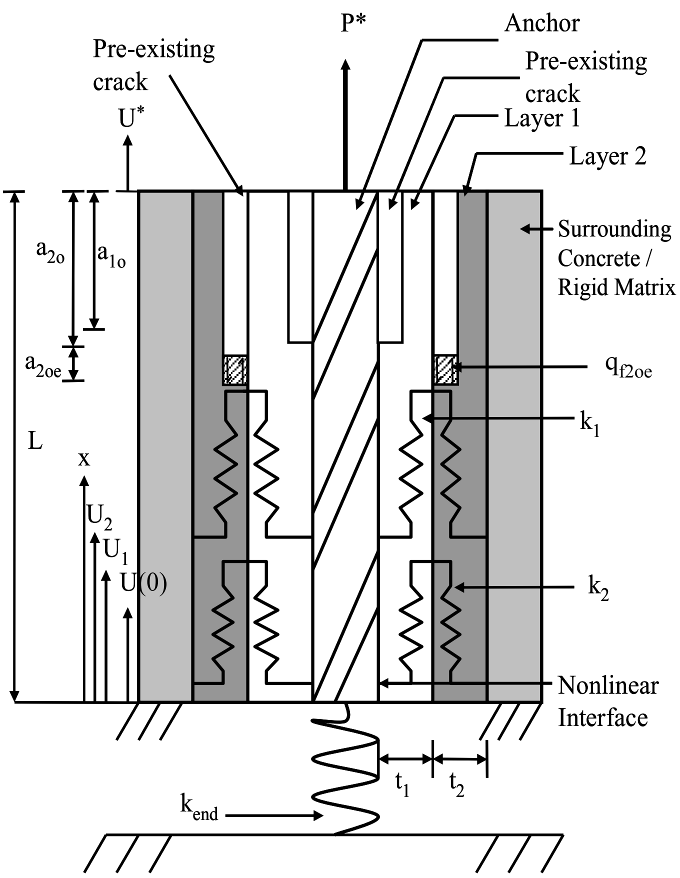

Figure 1. Multi-layer pull-out model of anchor.

In Figure 1, a_{1o} and a_{2o} are the lengths of pre-existing cracks. The bond stress and the shear resistance in the pre-existing crack portion are assumed to be zero. Furthermore it is assumed that the first layer crack is constant in length and does not propagate while in the second layer crack de-bonding has occurred as represented by the length a_{2oe} where a constant frictional shear force is acting as shown by $q_{f2oe}=Dq_{y2}$ where q_{y2} is the yield stress of the second interface and D is the reduction factor. t_1, t_2 and k_1, k_2 represent the thickness and stiffness of the first and second layers respectively.

2.2 *Analytical solution*

Figure 2 depicts a conceptual diagram of the anchor pull-out in which a vertical force P is applied at the top of an anchor bar. It is assumed that de-bonding has occurred over a length $a_{2oe,}$ starting at $x = L - a_{2o}$ and that a constant shear stress is acting along the de-bonded interface. Furthermore

$$q_1 > q_{y1} \tag{1}$$

$$q_2 < q_{y2} \tag{2}$$

$$a_{1o} = \alpha\, a_{2o} \tag{3}$$

where q_1, q_2 and q_{y1}, q_{y2} are the bond stress and the yield stress of the first and second layers respectively. The ratio of bond stress to the yield stress shown in equation 4 is verified throughout the calculations where the yield stress of the second layer is taken as 1/10th of the yield stress of the first layer. α is the controlling factor relating the pre-existing crack lengths. Now the equilibrium conditions at the interface of the first and second layer can be written as

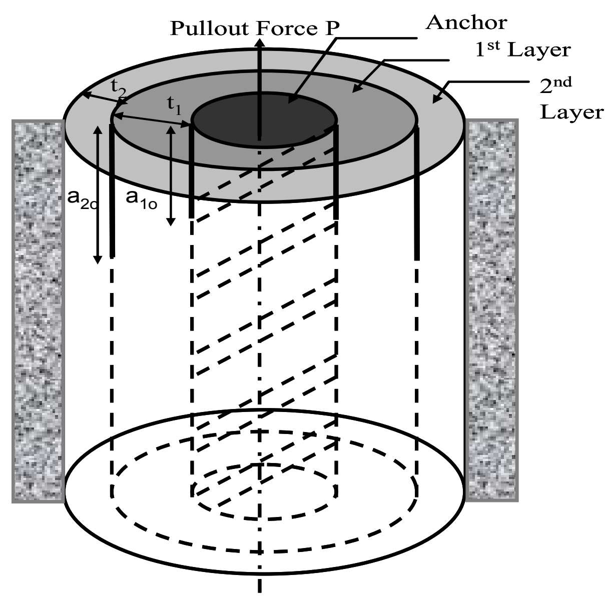

Figure 2. Conceptual diagram of the anchor pull-out model.

$$\frac{q_1}{q_{y1}} < \frac{q_2}{q_{y2}} \quad (4)$$

$$k_1 U_1 = k_2 U_2 \qquad 0 < x < (L\text{-}a_{2oe}) \quad (5)$$

$$k_1 U_1 = q_{f2oe} \qquad (L\text{-}a_{2oe}) < x < (L\text{-}a_{2o}) \quad (6)$$

$$q_1 = q_2 = q_{f1} = q_{f2} = 0 \quad (L\text{-}a_{2o}) < x < L \quad (7)$$

where q_{f1} and q_{f2} are frictional shear resistance in the pre-existing cracked portion, and U_1, U_2 are the pull-out displacement at the top of each infill layer. The equilibrium equation for the first layer can be written as

$$P_{,x} - q_{1o} = 0 \quad (8)$$

where q_{1o} is the frictional shear force per unit length acting on the anchor. A comma preceding a subscript represents a differential operator, i.e., $(\ )_{,x}$ is the derivative with respect to x. Introducing the constitutive relationship for the anchor bar, the following equation is obtained

$$P = E_a A_a U_{,x} \quad (9)$$

where $E_a A_a$ is the anchor stiffness. Then, the following differential equations for U are obtained

$$U_{,xx} - \omega_1^2 U = 0 \qquad 0 < x < (L\text{-}a_{2o}) \quad (10)$$

$$U_{,xx} = 0 \qquad (L\text{-}a_{2o}) < x < (L\text{-}a_{1o}) \quad (11)$$

$$U_{,xx} = 0 \qquad (L\text{-}a_{1o}) < x < L \quad (12)$$

where the quantity ω_1 is defined as

$$\omega_1 = \sqrt{\frac{k_1\left(\dfrac{G_2 t_{L2} t_1}{G_1 t_{L1} t_2 + G_2 t_{L2} t_1}\right)}{E_a A_a}} \quad (13)$$

where G_1, G_2 are the modulus of rigidity of the infill layers. Introducing P^* as the pull-out force at $x = L$, the boundary conditions can be prescribed as

$$k_{end} U(0) = P(0) \quad (14)$$

$$E_a A_a U_{,x}(L) = P^* \quad (15)$$

The continuity conditions in the displacements and anchor load at $x = L - a_{2o}$ and $x = L - a_{1o}$ require

$$U(L - a_{2o})^- = U(L - a_{2o})^+ \quad (16)$$

$$U_{,x}(L - a_{2o})^- = U_{,x}(L - a_{2o})^+ \quad (17)$$

$$U(L - a_{1o})^- = U(L - a_{1o})^+ \quad (18)$$

$$U_{,x}(L - a_{1o})^- = U_{,x}(L - a_{1o})^+ \quad (19)$$

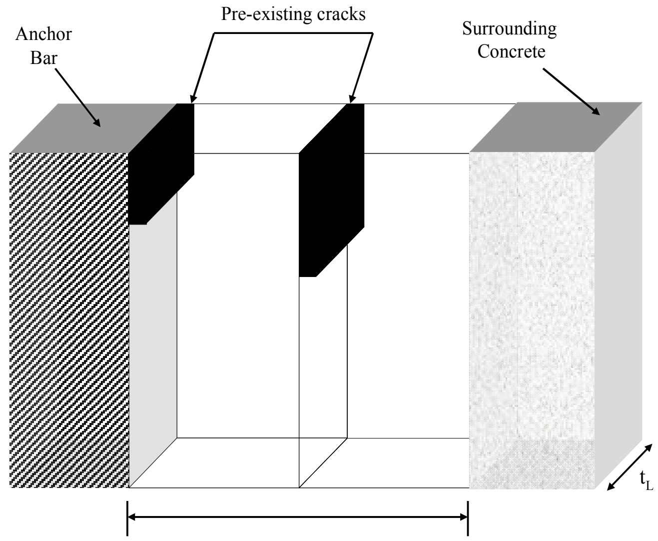

Figure 3. Brick element showing the multi-layer anchor pull-out model.

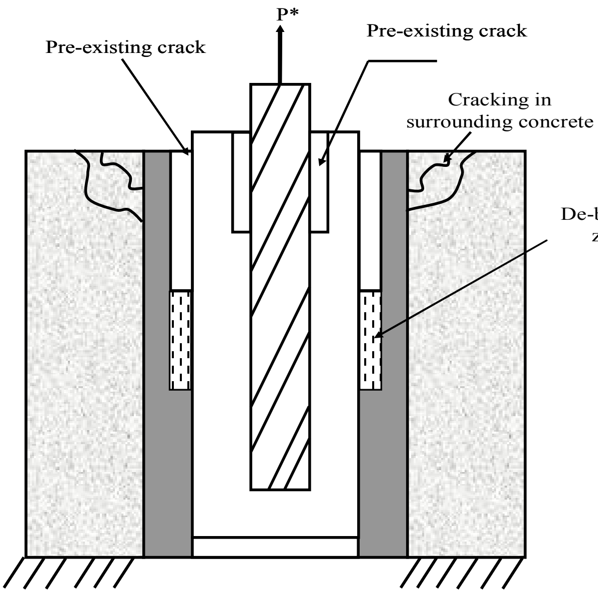

Figure 4. Steel reinforcement anchor bar pull-out mechanism.

Solving the above set of equations the solution for anchor bar pull-out load and pull-out displacement for the first layer is obtained. Figure 3 shows the schematic diagram of the brick element having multi-layer infilled material in between the steel reinforcement anchor bar and surrounding concrete. Figure 4 depicts the anchor bar pull-out mechanism where the anchor bar is pulled out by the application of vertical force in the upward direction accompanied by damage to the surrounding concrete. The crack in the second layer propagates beyond the pre-existing crack zone. The equilibrium equation for the second layer of the infilled material can be written as under where q_{2o} is the frictional shear force per unit length acting on the infill interface. Introducing the constitutive relationship for the anchor bar, the following equation is obtained.

$$P_{,x} - q_{2o} = 0 \tag{20}$$

$$P = E_a A_a U_{,x} + E_1 A_1 \left(\frac{G_2 t_{L2} t_1}{G_1 t_{L1} t_2 + G_2 t_{L2} t_1}\right) U_{,x} \tag{21}$$

$$E_E A_E = E_a A_a U_{,x} + E_1 A_1 \left(\frac{G_2 t_{L2} t_1}{G_1 t_{L1} t_2 + G_2 t_{L2} t_1}\right) \tag{22}$$

Then, the following differential equations for U are obtained

$$U_{,xx} - \omega_2^2 U = 0 \qquad 0 < x < (L\text{-}a_{2oe}) \tag{23}$$

$$U_{,xx} - \frac{q_{f2oe}}{E_E A_E} = 0 \qquad (L\text{-}a_{2oe}) < x < (L\text{-}a_{2o}) \tag{24}$$

$$U_{,xx} = 0 \qquad (L\text{-}a_{2o}) < x < L \tag{25}$$

where the quantity ω_2 is defined as

$$\omega_2 = \sqrt{\frac{k_2\left(\frac{G_1 t_{L1} t_2}{G_1 t_{L1} t_2 + G_2 t_{L2} t_1}\right)}{E_E A_E}} \tag{26}$$

The boundary conditions and the continuity conditions in the displacements and anchor load at $x = L - a_{2oe}$ and $x = L - a_{2o}$ require

$$U_1 = U_2 \tag{27}$$

$$q_2 = 0 \tag{28}$$

$$U(L - a_{2oe})^- = U(L - a_{2oe})^+ \tag{29}$$

$$U_{,x}(L - a_{2oe})^- = U_{,x}(L - a_{2oe})^+ \tag{30}$$

$$U(L - a_{2o})^- = U(L - a_{2o})^+ \tag{31}$$

$$U_{,x}(L - a_{2o})^- = U_{,x}(L - a_{2o})^+ \tag{32}$$

Solving the above set of equations the solution for the steel anchor bar pull-out load and pull-out displacement are obtained as follows

$$U(x) = \frac{P^* - q_{f2oe} a_{2oe}}{E_E A_E \omega_2} \left\{ \frac{\sinh\omega_2 x}{F_2} + \frac{\cosh\omega_2 x}{F_1} \right\} \qquad 0 < x < (L\text{-}a_{2oe}) \tag{33}$$

$$U(x) = \frac{q_{f2oe} x^2}{2E_E A_E} + \frac{P^* - q_{f2oe} L}{E_E A_E} x - \frac{q_{f2oe}(L - a_{2oe})^2}{2E_E A_E} + \frac{P^* - q_{f2oe} a_{2oe}}{E_E A_E \omega_2}(F_3) - \frac{P^* - q_{f2oe} L}{E_E A_E} L \qquad (L\text{-}a_{2oe}) < x < L \tag{34}$$

$$F_1 = \frac{k_{end}}{E_E A_E \omega_2} \cosh\omega_2 (L - a_{2oe}) + \sinh\omega_2 (L - a_{2oe})$$
$$F_2 = \cosh\omega_2 (L - a_{2oe}) + \frac{E_E A_E \omega_2}{k_{end}} \sinh\omega_2 (L - a_{2oe}) \tag{35}$$

$$F_3 = \frac{\cosh\omega_2 (L - a_{2oe})}{F_1} + \frac{\sinh\omega_2 (L - a_{2oe})}{F_2} \tag{36}$$

Then the value of the displacement of the steel anchor bar U^* and the pull-out load P^* can be expressed as follows

$$U^* = \frac{P^* - q_{f2oe} a_{2oe}}{E_E A_E \omega_2}(F_3) + \frac{P^* - \frac{1}{2} q_{f2oe} a_{2oe}}{E_E A_E} a_{2oe} \tag{37}$$

$$P^* = q_{f2oe} a_{2oe} + \frac{q_{y2}}{\omega_2} \left\{ \frac{F_1 F_2}{F_4} \right\} \tag{38}$$

$$F_4 = F_1 \sinh\omega_2 (L - a_{2oe}) + F_2 \cosh\omega_2 (L - a_{2oe}) \tag{39}$$

3 SENSITIVITY ANALYSIS AND OPTIMIZATION

3.1 *Influence of shear strength*

Figure 5 shows a three-dimensional diagram of a concrete bridge pier retrofitted by using post-installed steel reinforcement anchor bars. The encircled portion depicts the anchor infilled material along with the anchor bar where the damage is concentrated, surrounded by the footing concrete where the damage is to be minimized. The r/L ratio is taken as 1/40 where r is the radius of the anchor bar taken equal to 1mm and L is the anchor embedment length taken as 20 time diameter of the bar, d_b. $r = t_1 + t_2$ where t_1 and t_2 are the thickness of the inner and outer infill layer taken equal to $L/80$ each. The coefficient D expresses the shear transfer capability which depends on the surface condition of the debonded zone and is taken equal to 0.5. The ratio between the pre-existing crack length $\alpha = a_{2o}/a_{1o} = 1.0$ where a_{2o} and a_{1o} are taken as 5% of L. The pre-existing crack represents an artificial slit used to clearly identify the starting point of the crack and to stabilize the crack propagation direction. Damage W is assumed to be proportional to the strain energy in the most external infill layer which when exceeds the critical value damage is assumed to have occurred, given as

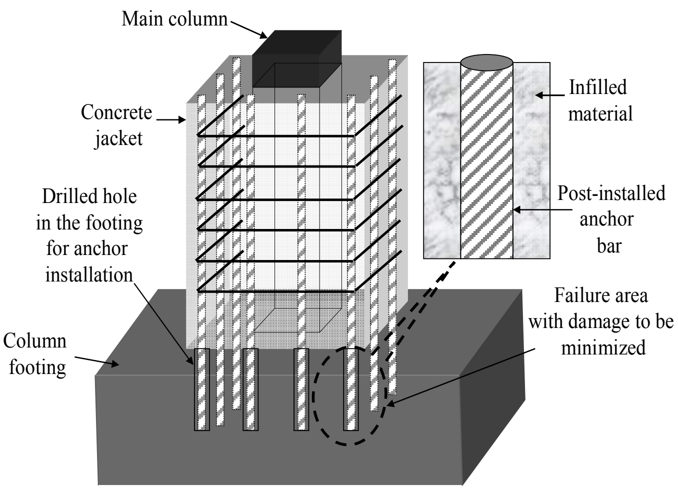

Figure 5. Three-dimensional view of a concrete bridge pier retrofitted using post-installed steel reinforcement anchor bars with the damage area to be minimized.

$$W = \frac{\tau^2}{2G_2} \tag{40}$$

where G_2 is the modulus of rigidity of the most external infill layer, τ is the shear stress at the interface of infilled material and surrounding concrete calculated as

$$\tau = X_1 \left\{ \begin{array}{l} \dfrac{\left(P^* - q_{f2oe}a_{2oe}\right)}{E_E A_E} \dfrac{cosh\,\omega_2 x}{cosh\,\omega_2\left(L - a_{2oe}\right)} \\ - X_2\, sinh\,\omega_2 x\, tanh\,\omega_2\left(L - a_{2oe}\right) \\ + X_2\, cosh\,\omega_2 x \end{array} \right\} \tag{41}$$

$$X_1 = \frac{k_2}{t_2}\left(\frac{G_1 t_{L1} t_2}{G_1 t_{L1} t_2 + G_2 t_{L2} t_1}\right) \tag{42}$$

$$X_2 = \frac{\left(P^* - q_{f2oe}a_{2oe}\right)}{F_2 k_{end}} \tag{43}$$

The damage is normalized by dividing it with

$$W_o = \frac{q^2_{y2max}}{2G_2} \tag{44}$$

where q_{y2max} is the maximum value of the yield stress of the second layer and the $q_{y2max}/\,q_{y2}$ ratio is taken as 2.0. All the material constants in this study are set dimensionless and the ratio of the elastic modulus of the infill material to the shear strength E_1/q_{y1} is kept constant equal to 30. Also the ratio of the elastic modulus of the anchor bar to the infill material E_a/E_1 is kept constant at 100.These ratios are kept constant throughout the analysis.

The influence of shear strength ratio q_{y2}/q_{y1} of the infilled material on the pull-out behavior of the anchor bar is shown in Figures 6-9. From the figures it is clear that the shear strength ratio of the interface has a significant effect on these relationships.

In the figures the shear strength ratio q_{y2}/q_{y1} of the infilled material is changed as 1 (base value), 0.7, 0.5, and 0.2. The effect of shear strength ratio on peak pull-out load and displacement is shown in Table 1. From the figures it is seen that the initial displacement of the anchor bar is large, this phenomenon is attributed to the presence of pre-existing crack portion which leads to a large initial displacement.

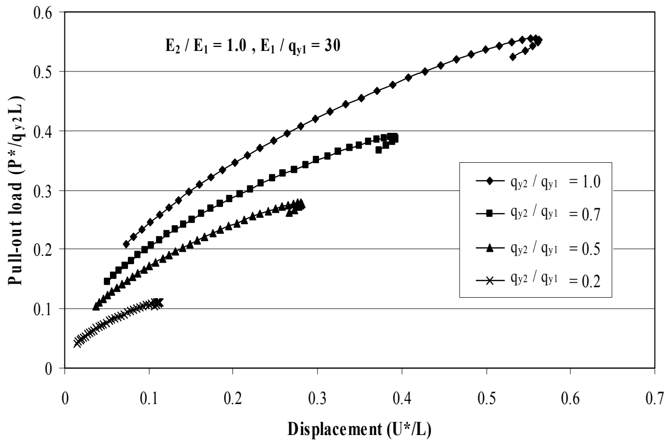

Figure 6. Effect of q_{y2}/q_{y1} ratio on load-displacement curve.

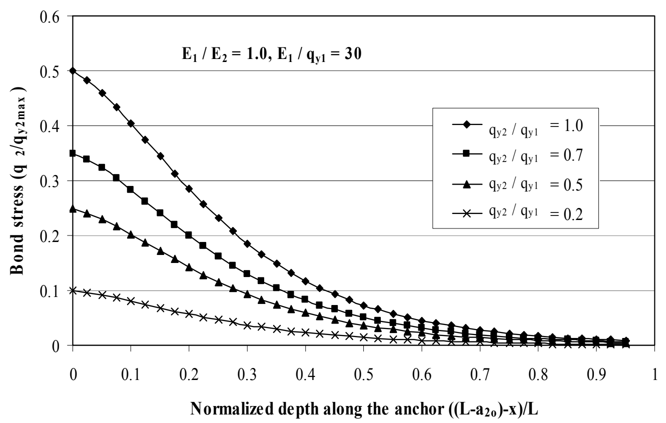

Figure 7. Effect of q_{y2}/q_{y1} ratio on bond stress.

The results show that the peak pull-out displacement increases as the shear strength ratio of the interface increases but starts to decrease after reaching within 85% of L implying the effect of the elastic modulus to the shear strength ratio. Similarly in the Figure 7 and Figure 8 that the slope of the curve also changes after reaching a certain inflection point, this phenomenon is also attributed to the elastic modulus to shear strength ratio of the infill material. The increase in pull-out displacement means that the residual displacement also increases, which is not desirable from the viewpoint of reducing the damage caused in the concrete jacketed bridge pier footing. From the above results and discussion it can be concluded that the shear strength should be set small in the range where the required pull-out load is achieved but the residual displacement is minimized leading to a reduced damage zone in the pier footing.

Table 1. Effects of q_{y2}/q_{y1} ratio on peak pull-out load and displacement.

Shear strength (q_{y2}/q_{y1})	Load ($P^*/q_{y2}L$)	Displacement (U^*/L)
0.2	0.11	0.12
0.5	0.27	0.28
0.7	0.38	0.39
1.0	0.55	0.56

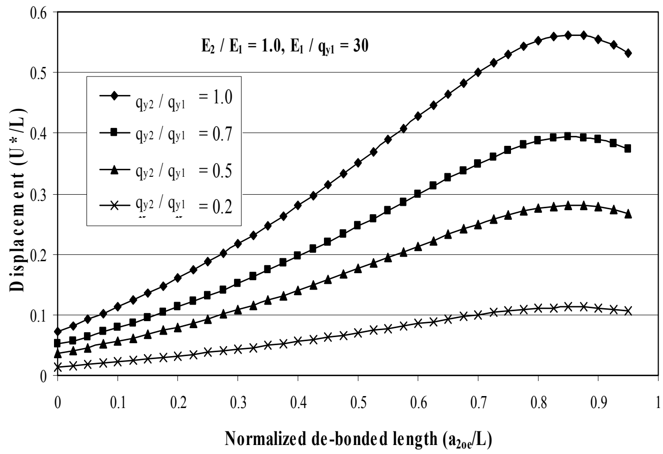

Figure 8. Effect of q_{y2}/q_{y1} ratio on de-bonded length.

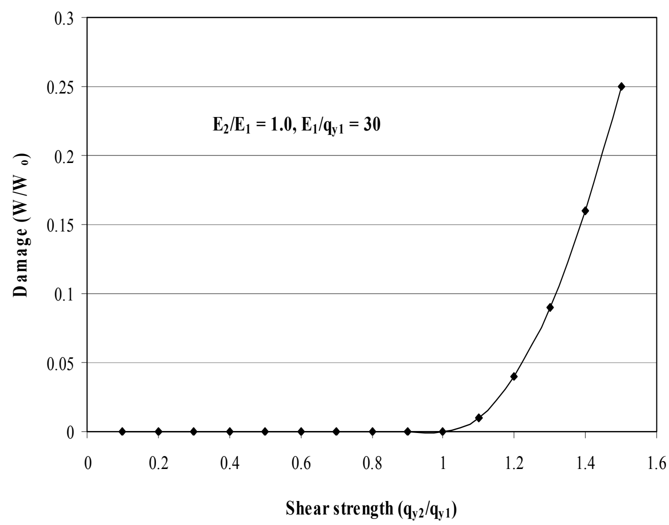

Figure 9. Effect of q_{y2}/q_{y1} on damage to surrounding concrete.

3.2 *Influence of elastic modulus*

The influence of the elastic modulus of the interface, E, on the overall pull-out behavior of the anchor bar has been shown in the Figures 10-13. The shear strength ratio q_{y2}/q_{y1} of the first and the second layer are kept constant equal to 1.0. The ratio of elastic modulus to the shear strength E_1/q_{y1} is kept equal to 30. From the figures it is clear that elastic modulus ratio of the interface has a vital role in reducing the peak pull-out displacement. The elastic modulus ratio E_2/E_1 of the interface is changed as 0.1 (base value), 0.5, 1.0, and 2.0. It is confirmed that the pull-out load displacement relationship is significantly influenced by varying this parameter.

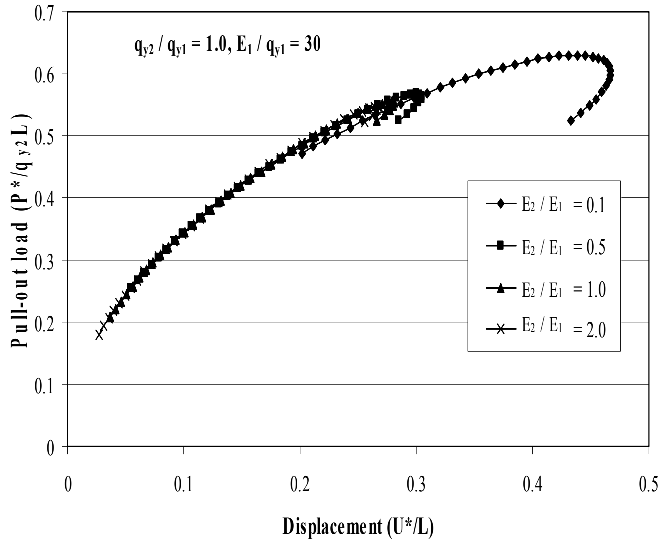

Figure 10. Effect of E_2/E_1 ratio on load-displacement curve.

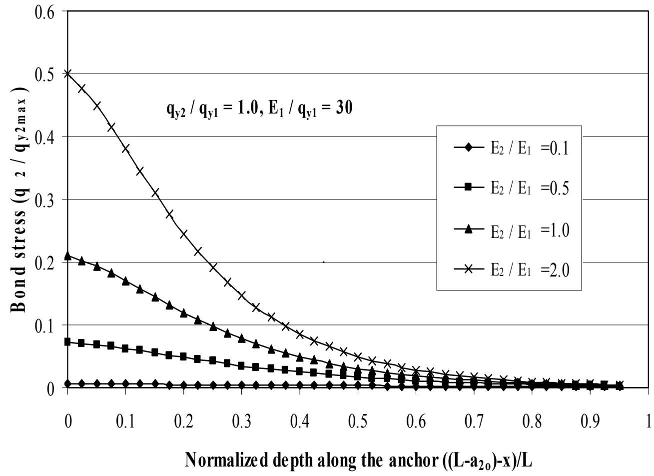

Figure 11. Effect of E_2/E_1 ratio on bond stress.

From the figures it is seen that the initial pull-out displacement is large, this phenomenon is attributed to the presence of pre-existing crack. It is seen that the peak pull-out displacement reduces as the elastic modulus ratio of the interface increases but starts to decrease after reaching within 75% of L implying to the effect of the elastic modulus to the shear strength ratio. From the results it is noted that E_2/E_1 ratio of 0.1 is the critical case for which the steepest inflection point is seen. Also in the Figure 11 and Figure 12 the change of slope implies to the effect of elastic modulus to the shear strength ratio. Table 2 shows the effect of E_2/E_1 on pull-out load and displacement. The effect of elastic modulus is also significant for the damage caused into the surrounding footing. It is confirmed that there is a tendency that damage can be minimized by varying the elastic modulus ratio of the interface zone.

From the above facts and discussion it can be concluded that the elastic modulus of the interface zone should be kept large to reduce the residual displacements thus minimizing the damage caused in the surrounding footing concrete.

Table 2. Effect of E_2/E_1 ratio on peak pull-out displacement.

Elastic Modulus (E_2/E_1)	Load ($P^*/q_{y2}L$)	Displacement (U*/L)
0.1	0.63	0.44
0.5	0.56	0.30
1.0	0.55	0.27
2.0	0.54	0.26

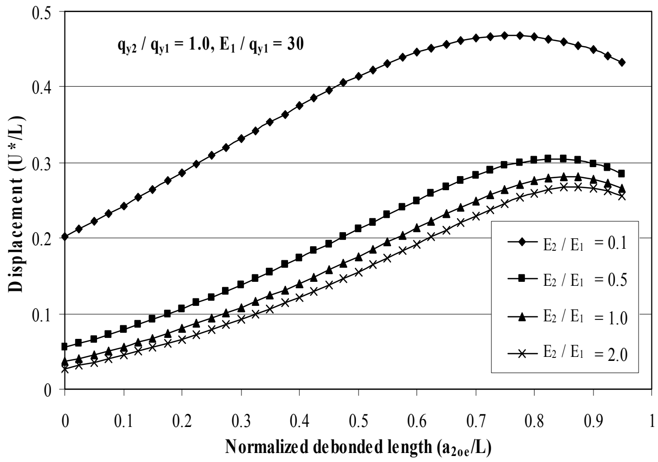

Figure 12. Effect of E_2/E_1 ratio on the de-bonded length.

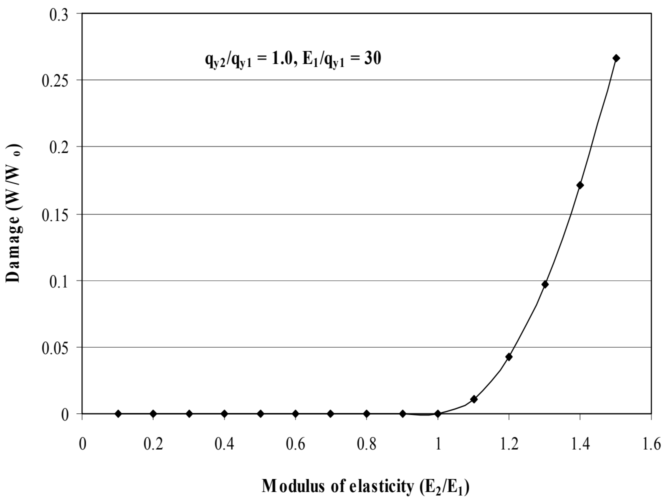

Figure 13. Effect of E_2/E_1 on damage to surrounding concrete.

3.3 *Influence of pre-existing crack*

From the analytical simulation result shown in Figure 14 it turns out that the presence of pre-existing crack has a critical effect on pull-out load displacement relationship. Although pre-existing crack represents an artificial slit used for identifying the crack location and its stabilized propagation but the presence of pre-exiting crack reduces the maximum pull-out load and displacements. However the displacements corresponding to the model without the pre-existing crack increases. The amount of reduction depends on the length of the pre-existing crack. Therefore it can be concluded that it is undesirable to have a pre-existing crack in the interface zone.

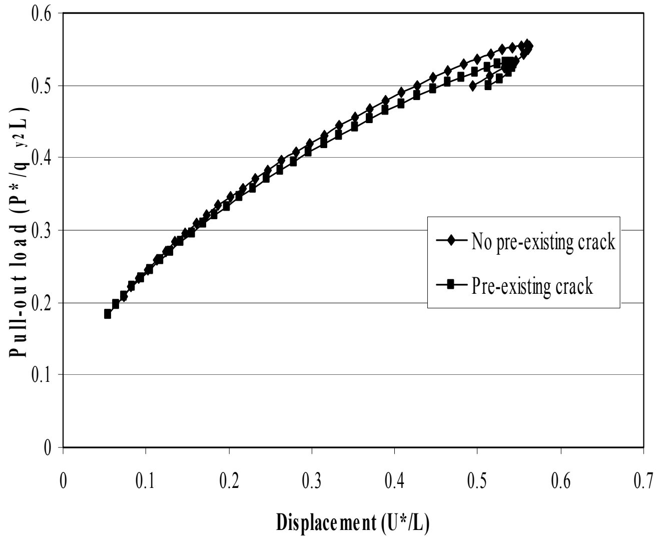

Figure 14. Effect of pre-existing crack on pull-out load displacement relationship.

3.4 *Optimum interface properties*

For the case of the anchor bar used in strengthening reinforced concrete bridge piers, it is desirable that the residual displacement is reduced which lead to ultimately reduced damage to the surrounding footing concrete. Keeping in mind this point of view the

$$f = w_1 x_1 + w_2 x_2 \tag{45}$$

$$x_1 = \frac{U^*}{U^*_{max}} \tag{46}$$

$$x_1 = \frac{W}{W_{max}} \tag{47}$$

present analytical study shows that the shear strength of the infilled material should be small in the range satisfying the required pull-out load but minimizing- the residual displacements and the elastic modulus of the infilled material should be kept high to reduce the residual displacement. This optimum condition has been defined in the form of an objective function as shown above. w_1 and w_2 are the weighted constants having value equal to 0.5 each. The optimum interface properties are defined as the set of properties which lead to the minimum value of the objective function. Figure 15 shows the objective function along with the parameter set number. It is seen that when the elastic modulus and the shear strength of the outer most infill layer is kept smaller than those of the first layer, then the objective function reduces to its minimum value which corresponds to the optimum failure condition and the corresponding parameters represent the optimum interface properties.

Table 3. Parameter set number and objective function.

Param. set no.	$\frac{E_2}{E_1}$	$\frac{q_{y2}}{q_{y1}}$	x_1	x_2	f
1	0.20	0.90	0.695	0.035	0.365
2	0.30	0.85	0.637	0.056	0.346
3	0.40	0.80	0.735	0.096	0.416
4	0.50	0.75	0.790	0.156	0.473
5	0.60	0.70	0.840	0.251	0.546
6	0.70	0.65	0.910	0.431	0.671
7	0.80	0.60	1.000	1.000	1.000

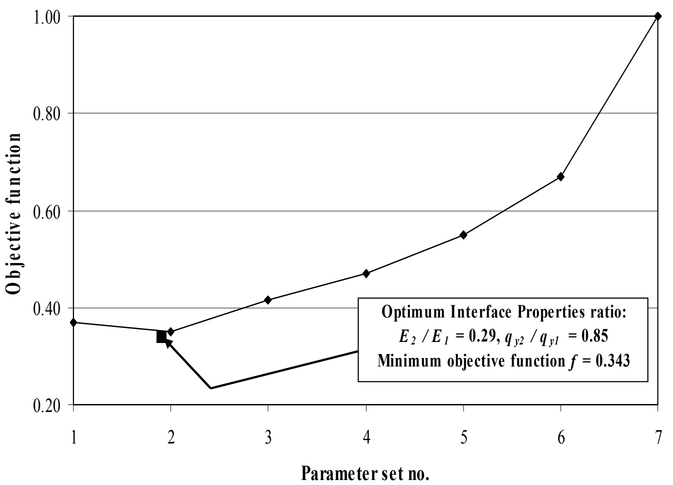

Figure 15. Relationship between objective function and parameters set number.

Table 3 depicts the values of the parameters along with the objective functions. The values of x_1 and x_2 correspond to the lowest value of pull-out load obtained from the combination of parameters. From Table 3 it can be seen that the optimum interface properties point lies somewhere between E_2/E_1 ratio 0.2 to 0.4 and q_{y2}/q_{y1} ratio 0.9 to 0.8, as these give the lowest value of the objective function. So keeping in mind this point further parametric investigation was carried out to find out the exact value of the optimum interface properties ratio. From the analysis it was found that the optimum interface properties ratio lies at the value of E_2/E_1 at 0.29 and q_{y2}/q_{y1} at 0.85 which leads to the minimum value of objective function f at 0.343. Hence from the above facts and discussion it can be concluded that the combination of optimum interface properties leads to the minimized objective function which is the desired failure condition. The multi-layer structure of the infilled material is considered effective in controlling the pull-out behavior.

4 CONCLUSIONS

The influence of the interface properties of the infilled material on the pull-out behavior of the post-installed anchor bar has been investigated using a multi-layer analytical model having pre-existing crack and de-bonding at the top. The properties of the interface between the anchor bar and the matrix and that between the infill layers were changed to study the effect of these parameters on the overall behavior. From the present study the following conclusions can be drawn.

It is desirable to make the elastic modulus of the interface material larger to reduce the pull-out displacement thus resulting in reduced damage to the surrounding footing concrete.

It is effective to make the shear strength of the interface material large to increase the pull-out load. The low interface shear strength, however, reduces the damage caused in the footing concrete, if the interface shear strength is enough to keep the bond stress up to the yielding of anchor.

The optimum interface properties of post-installed anchor bars are effective in reducing maximum pull-out displacement of the anchor up to 36% and reducing the damage caused to the surrounding footing concrete up to 95%.

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