UNIVERSITY OF GAZIANTEP

GRADUATE SCHOOL OF

NATURAL AND APPLIED SCIENCES

USE OF SOFT COMPUTING TECHNIQUES FOR PREDICTING SHEAR STRENGTH OF ADHESIVE ANCHORS

M.Sc Thesis
In
CIVIL ENGINEERING

BY
MUHAMMET ENES YILMAZ
JANUARY 2013

Use of Soft Computing Techniques for Predicting Shear Strength of Adhesive Anchors

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In
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Supervisor
Assoc. Prof. Dr. Mehmet Gesoğlu

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T.C.
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Muhammet Enes YILMAZ

ABSTRACT

Use of Soft Computing Techniques for Predicting Shear Strength of Adhesive Anchors

Muhammet Enes Yılmaz

M. Sc. in Civil Engineering

Supervisoor: Associated Prof. Dr. MEHMET GESOĞLU

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This paper reports the results of an analytical study to predict the edge breakout shear capacity of single adhesive anchors post-installed into uncracked hardened concrete. For this purpose, an experimental database for the adhesive anchors compiled by the ACI Committee 355 was obtained and utilized to construct training and test sets so as to derive the closed-form solution by means of gene expression programming (GEP). The independent variables used for development of the prediction model were anchor diameter, type of anchor, edge distance, embedment depth, clear clearance of the anchor, type of chemical adhesive, method of injection of the chemical, and compressive strength of the concrete. The generated prediction model yielded correlation coefficients of 0.98 and 0.92 for training and testing data sets, respectively. Moreover, the performance of the proposed model was compared with the existing models proposed by American Concrete Institute (ACI) and Prestressed/Precast Concrete Institute (PCI). The analyses showed that the proposed GEP model provided much more accurate estimation of the observed values as compared to the other models.

Keywords: Adhesive anchors, Genetic programming, Modeling, Shear capacity

ÖZET

Kimyasal Ankrajlarda Kesme Kuvvetinin Bilgisayar Programlamlarıyla Tahmin Edilmesi

Muhammet Enes Yılmaz

İnşaat Mühendisliği Yüksek Lisans

Danışman: Doç. Dr. MEHMET GESOĞLU

Ocak 2013, 44 sayfa

Bu çalışma tek bir yapıştırıcıyla çatlamamış sertleşmiş betonun içine sonrası yüklenmiş Ankrajlarin kenar koparma kesme kapasitesini tahmin etmek için analitik bir çalışmanın sonuçlarını açıklamaktadır. Bu amaç için, ACI Komite 355 tarafından oluşturulan yapışkan Ankrajlarin için bir deney veri tabanı elde edilmiş ve eğitim ve test gen ekspresyonu programlama (GEP) vasıtası ile, kapalı-formda çözümü elde edecek şekilde ayarlar oluşturmak için kullanılmıştır. Tahmin modeli geliştirilmesi için kullanılan bağımsız değişkenler ankrajın çapı, ankraj türü, kenar mesafesi, gömme derinliği, ankraj net açıklığı, kimyasal yapıştırıcı, kimyasal enjeksiyon yöntemi ve beton basınç dayanımı tipleridir. Oluşturulan tahmin modeli korelasyon katsayıları sırasıyla eğitim ve test veri kümeleri için 0.98 ve 0.92 bulunmuştur. Ayrıca, önerilen modelin performansı Amerikan Beton Enstitüsü (ACI) ve Öngerilmeli / Prefabrik Beton Enstitüsü (PCI) tarafından önerilen mevcut modelleri ile karşılaştırılmıştır. Analiz diğer modellere göre önerilen GEP modelinde gözlenen değerler arasında çok daha doğru bir tahminini sağladığı görülmüştür.

Anahtar Kelimeler: Yapıştırıcı çapa, Genetik programlama, Modelleme, Kesme kapasitesi

To My Family, they should receive my greatest appreciation for their enormous love. They always respect what I want to do also give me their full support encouragement over the years.

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LIST OF SYMBOLS

MEA	Mechanical Expansion Anchors
ANN	Artificial Neural Network
GP	Genetic Programming
GEP	Gene-Expression Programming
ET	Expression Tree
SSC	Self-Compacting Concrete
GA	Genetic Algorithms

CHAPTER 1

INTRODUCTION

1.1 General

The main purpose of using metallic anchorage systems in concrete structures is to attach objects. Extensively used are anchor bolts which are used on all types of projects from buildings to dams and nuclear power plants, also they can be used to firmly fix embedded plates to a concrete foundation when used with a structural steel element. They are subjected to many different load combinations such as tension, shear, impact, fatigue and seismic loads. The reason of using these anchorage systems is because of the demand for more flexibility in planning, design and strengthening of the concrete structures. Another use of this anchor bolt is to connect the concrete foundation of a building to its wall. With this, the building is more resistant to earthquakes.

The push over the last two decades to reduce construction duration has brought about increased use of fasteners for the transfer of concentrated loads in concrete structures. Various types of fastenings, such as cast-in-place headed anchors, as well as post-installed anchorage systems are available to meet a wide range of strength and application requirements. Furthermore, installation techniques have been developed for certain fastening systems, which have properties that can be tailored to fit special construction situations and offer some constructability and productivity advantages.

Anchors used to attach objects in concrete structures can be divided into two main general categories: cast-in-place and retrofit. Cast-in place anchors may be classified into three groups: non-adjustable embedded anchors, bolted connections which consist of headed bolts and adjustable anchors. Retrofit anchors are subdivided into expansion anchors, bonded anchors and undercut anchors. These categories will be explained widely in chapter 2.

1.2 Research Objectives

This study concerns the investigation of the load-deflection behavior and ultimate capacities of concrete anchorage systems under shear loading. The anchors used in this study were adhesive type. A data set regarding the shear capacity was obtained from ACI commute.

Experimental values for ultimate loads of the anchors were also compared with the characteristic values suggested obtained from the formula in ACI 349 standard as well as genetic programming. For this, a model was constructed using GEP approach.

1.3 Thesis Organization

This thesis consists of four chapters.

Chapter 1 is an introduction about the usage of anchorage systems in concrete structures.

Chapter 2 gives information about the literature review and general background information about the anchorage systems and the two main categories of anchoring devices.

Chapter 3 covers the methodology conducted throughout this study.

Chapter 4 is available formulations for estimating shear capacity

Chapter 5 gives results and discussions

Chapter 6 consists of conclusion paragraph and some recommendation for the future studies.

CHAPTER 2

LITERATURE REVIEW AND BACKGROUND

2.1 Post – Installed Anchors

There are two main types of post-installed anchors – Mechanical Expansion Anchors (MEA) and Bonded Anchors.

2.1.1 Mechanical Expansion Anchors

MEAs are inserted in pre-drilled holes. These anchors expand and bear against the concrete surface and are placed using any of the following techniques:

a) Hammering the anchor (deformation controlled)

b) Tightening a nut (torque controlled)

c) Expanding into an undercut (expanding into a notched opening at the bottom of a hole).

MEAs are frequently used to anchor minor or temporary attachments such as signs, brackets, inspection ladders, safety railing, utility pipes and light fixtures to hardened concrete.

MEAs have the following advantages:

- Are inexpensive
- Are quick and easy to install
- Can be installed in any orientation
- Loading can be applied immediately after installation

MEAs have the following disadvantages:

- Have relatively small tensile strength

- Are not recommended for use in tension zone where concrete is likely to crack

- Are not suitable for resisting dynamic (vehicle loading, seismic etc.) or vibratory loads

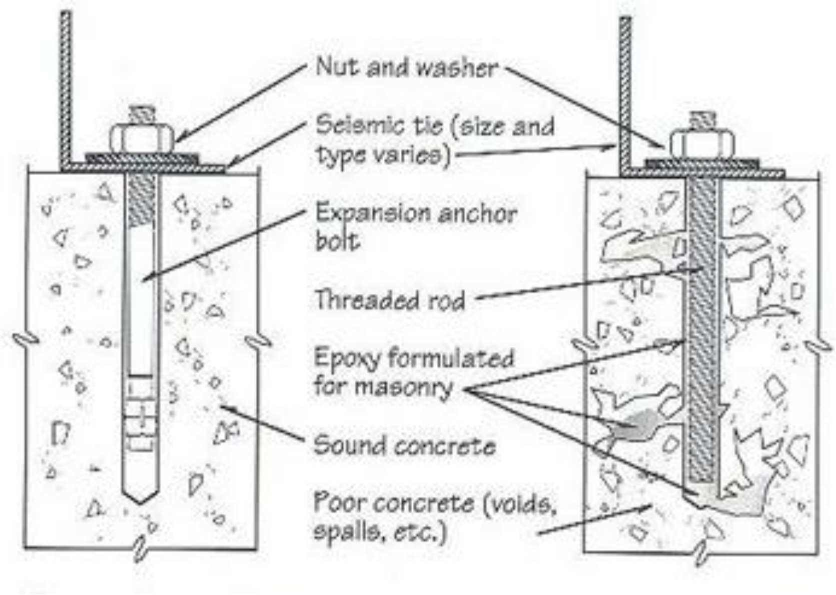


Figure 2.1: Common Types of MEAs (UHG 1993)

2.1.2 Bonded Anchors

Bonded anchor systems include the following:

2.1.2.1 Drill and Bond Dowel:

Mag-phos concrete hardens or cures in about three hours and does not require any special treatment during curing. It also develops full strength in three days.

Mag-phos has the following advantages:

- Has relatively high tensile strength

- Has quick setting time

- Exhibits minimal shrinkage.

Mag-phos has the following disadvantages:

- Cannot come into contact with zinc, aluminum, copper or cadmium (e.g., Mag-phos cannot be used for galvanized anchors)

- Is not likely to be fully effective in cracked concrete

2.1.2.2 Drill and Grout Dowel:

Neat portland cement paste (grout) is used as a bonding agent. Generally, cement grout is less expensive than mag-phos concrete, but cures more slowly. Grout has to be cured for at least three days during which time the dowels should not be disturbed.

The grout normally develops 50% of its strength in three days, and reaches full strength in about 28 days. In addition, grout has a tendency to shrink – leading to cracks.

2.1.2.3 Drill and Epoxy Bond Dowel:

Bulk epoxy is used as the bonding agent. This method of bonding anchors to concrete is no longer used in structural applications as several bulk epoxies exhibit high creep characteristics under sustained tensile loads. In addition these epoxies may require exact mix ratios and are sensitive to freeze/thaw conditions.

2.1.2.4 Drill and Bond Dowel (chemical adhesive):

A chemical adhesive or a cartridge epoxy is used as a bonding agent.

The advantages of chemical adhesives include:

- Higher viscosity (than mag-phos or grout) that helps the adhesive to be retained in a drilled hole

- Relatively quick setting time

- Low shrinkage

One of the disadvantages of this system is the need for stringent quality control and quality assurance testing, particularly since creep deformations can be a concern. The chemical adhesives in drill and bond applications must be pre-approved and listed under the “Authorized Material List” prior to use on Caltrans’ projects. Bonded anchors provide a simple, effective, economical and preferred system for attaching metal fixtures or new concrete to existing/hardened concrete.

In this system, bar reinforcement dowels or threaded rods are placed in drilled holes filled with either grout or a bonding material. Typically, bonded anchors are used for attaching new bridge barriers, sign frames or electroliers onto existing bridge decks, widening bridge abutments and bridge decks, and in seismic retrofits.

2.2 Adhesive Anchors

Resistance to tension loads is provided by the presence of an adhesive between the threaded rods (or rebar) and the inside walls of the drill hole.

2.2.1 Types of Adhesive Anchors

An adhesive anchor consists of a threaded rod or deformed bar installed in a hole drilled in main structure that is filled with a structural adhesive. For these anchors, the hole is typically 3-4 mm larger than the anchor diameter. The structural adhesive may be two-part chemical compound of polyesters, vinyl esters or epoxies and they are available in four forms: glass capsules, plastic cartridges, tubes, or bulk (ACI 1991)

Figure 2.2: A7 Adhesive (AWPH 2010)

Glass capsules are inserted into the drilled hole, and then broken by the anchor rod when it is rotated and hammered into place, thereby mixing two components to cause a chemical reaction.

The plastic cartridge is used with a dispenser and a mixing nozzle which mix the two parts, initiating a chemical reaction while installing the compound into the drilled hole. The anchor rod is then inserted into the hole completing the installation. The setting time is dependent on temperature.

The tube type contains two components which are mixed by kneading the tube, placing the mixture into the hole, and finally, inserting the anchor rod into the hole.

The bulk systems predominantly use epoxies, which are either premixed in a pot and used immediately, or pumped through a mixer and injected into the hole. The anchor is installed immediately afterward. Epoxies can be formulated to set up quickly or slowly (up to 36 hr curing time).

Among structural adhesives, epoxies are the most widely accepted and used. When compared to polyesters, acrylics and vinyl types, epoxies have lower shrinkage; hence reducing the residual stresses at the interface the operating principles of the adhesive anchors depends on gluing together a threaded rod and the wall of the drilled hole with reacting resins. The load is transferred through the adhesive to the base material along the entire embedded portion of the anchor. (Mays et. al.)

The adhesive anchor is preferable to other types of anchors in many aspects such as reduced cost, and time, and ease of installation. In addition, epoxies and other polymer resins are gaining popularity because of the more rapid cure compared to that obtained with portland cement grouts.

2.2.1.1 Expansion Anchors

Expansion anchors are the mechanical type anchors which are designed to be inserted into predrilled holes and then expanded by either tightening the nut (torque controlled expansion anchors) or hammering the anchor (deformation controlled expansion anchors). The anchor capacity depends on the friction at the anchor/wall interface and the mechanical interlock between the expanded portion of the anchor and the base material. Expansion anchors are classified as torque-controlled expansion anchors and deformation-controlled expansion anchors. Tension loads are transferred to the base material through a portion of the anchor that is expanded inside the drill hole.

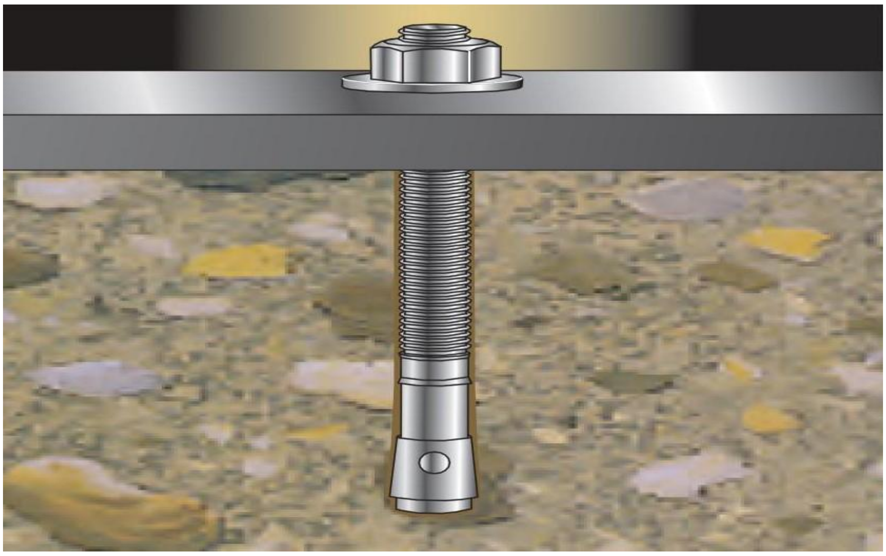


Figure 2.3: Dynabolts (AWPH 2010)

2.2.1.2 Undercut Anchors

Undercut anchors transfer forces into the structure by mechanical interlock with the base material. They all operate by keying and bearing against on undercut in the concrete at the bottom of the drilled hole. They cause little or no expansion force in the concrete but generate high-tensile loading capacities. The undercut may be formed by means of a special drilling operation before insertion or in conjunction with insertion and securing of the anchor.

2.2.1.3 Keying Type

Holding strength comes from a portion of an anchor that is expanded into a hollow space in a base material that contains voids such as concrete block or brick.

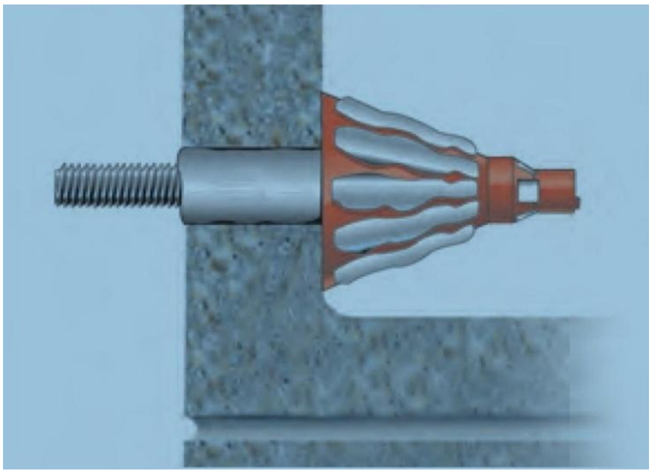


Figure 2.4: Adhesives used in screen tubes or umbrellas insert (AWPH 2010)

2.2.1.4 Friction Type

Load capacity is created by driving a fastener into a pre-drilled hole that is slightly smaller than the fastener itself.

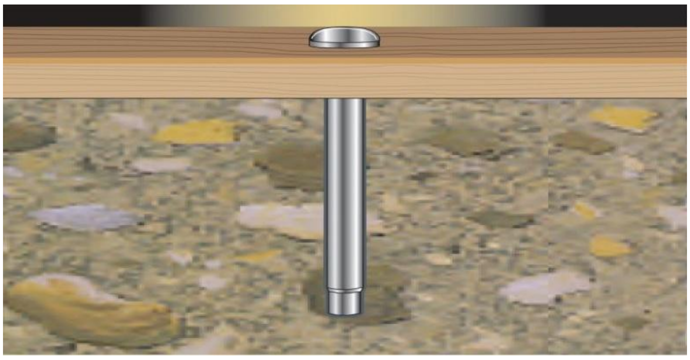


Figure 2.5: Redi-Drives (AWPH 2010)

2.2.1.5 Mechanical Interlocking Type

Tension loads are resisted by threads on the fastener engaging with threads cut into the base material.

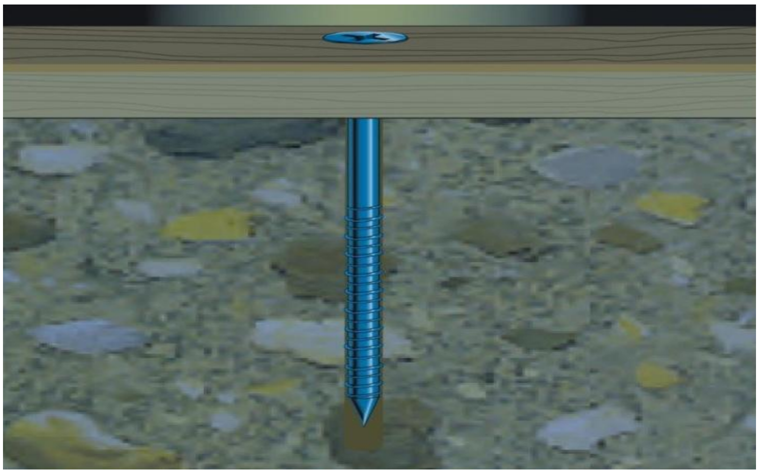


Figure 2.6: LDT Anchor (AWPH 2010)

2.2.2 Modes of Failure

When anchors are loaded to their maximum capacity, several different types (modes) of failure are possible depending on the type of anchor, strength of the base material, embedment depth, location of the anchor, etc.

Anchors are loaded through attachments to the embedded anchor in tension and shear or combinations of tension and shear. They may also be subjected to bending on the details of shear transfer through attachments. Dynamic loading can occur in machine foundations, bridges, pipelines and railway barriers. Fatigue loads or seismic load with varying magnitude and frequency may also act on the anchorage system.

In addition to the type of loading, failure mode of anchor systems is also important. Although the loading type is the dominant one, type of anchorage, the concrete strength, axial spacing of anchors and the edge distance also influence the failure mode. The following sections investigate the failure types of anchors systems both under tensile and shear loading, respectively.

2.2.2.1 Failure Modes Under Tension Loading

If the anchor system is subjected to tension, the anchor will fail through one of the following modes depending on several variables cited above.

a) Failure of Anchor Steel: Anchor steel failure (characterized by yielding and fracture of the steel) is likely to occur only with sufficiently long embedment lengths, (Cook, 1993) the capacity of the anchorage exceeds the tensile or shear strength of the steel anchor or rod material.

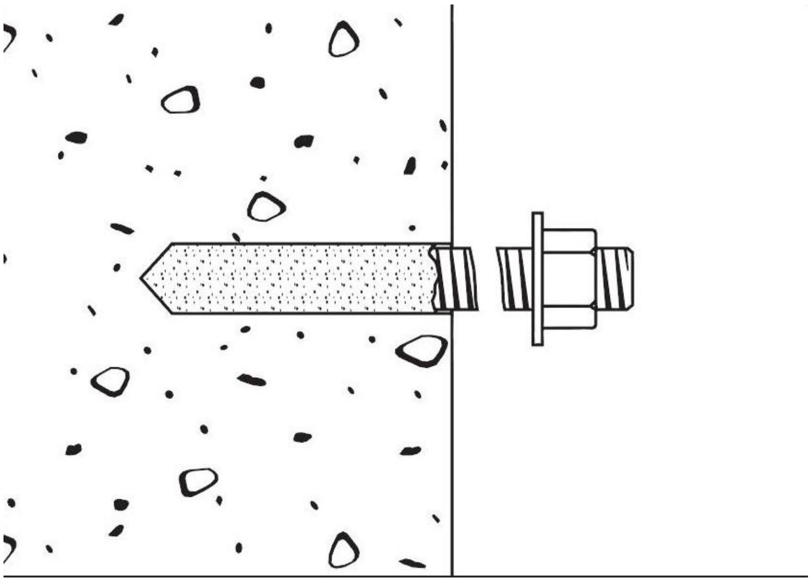


Figure 2.7: Failure of Anchor Steel (AWPH, 2010)

b) Pull-out of the Anchor: Pull-out or pull-through failures occur by sliding out of the fastening device or part of it from the concrete (pull-out) or by pulling a cone through the sleeve (pull-through) without breaking out of a fairly substantial portion of the surrounding concrete. The pull-out failure is generally observed in expansion anchors for which the failure load depends on the design of expansion mechanism, method of drilling the hole, condition of the drilled hole, and deformability (toughness) of the concrete (Fuchs et al., 1993) Pull-out or bond failures are also common for chemical and grouted anchors. This type of failure is usually accompanied by a shallow concrete cone with a depth up to one-half of the total stud embedment .Base material adjacent to the extension portion of an anchor crushes, resulting in the anchor pulling out of the hole until the capacity of the spall cone is reached, at which point the concrete will spall. This type of failure happens more commonly when anchors are set with deep embedment depths.

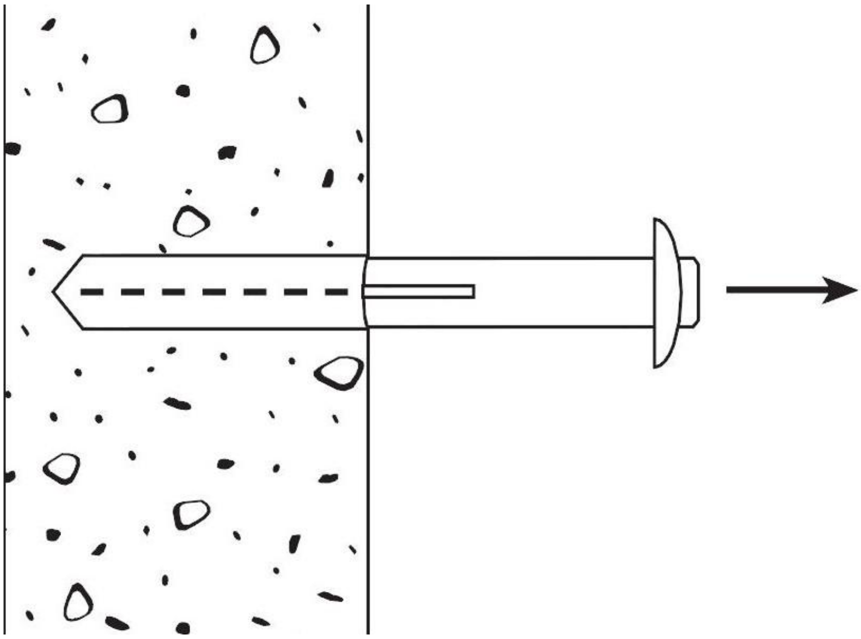


Figure 2.8: Pull-out of the Anchor (AWPH, 2010)

c) Concrete Cone Failure: When the embedment of an anchor or a group of anchors is insufficient to develop the tensile strength of the anchor steel a pull-out cone failure of the concrete is the principal failure mode The angle of the failure of cone, measured from the axis of the anchor, varies along the failure surface and shows considerable scatter. In ACI 349, the angle of the failure cone of bonded and expansion anchors is assumed as 45^{o}.

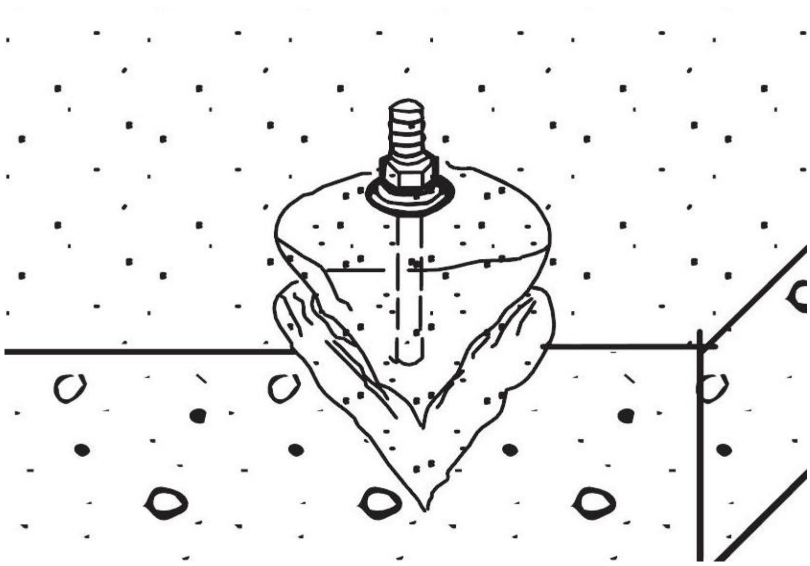


Figure 2.9: Concrete Cone Failure (AWPH, 2010)

d) Splitting of Concrete Failure: Anchors installed in thin, unreinforced slabs and beams may result in a split structural member where the concrete slab or beam fails in bending (Wiewel, 1991)

Splitting may lead either to complete split of the structural element, or to cracks between adjacent anchors or between the anchors and the edge.

e) Axial Spacing Failure: When the axial spacing of the individual anchors is small, concrete cones of the anchors may overlap to form a combined failure.

f) Edge Failure: If an anchor is located too close to an edge of the structural member, concrete cone that forms around the anchor extends to the edge causing an edge fracture.

Reduces the holding values, when anchors are placed too close to the edge. This also occurs when two or more anchors are spaced closely together. See suggested edge distance, anchor spacing distances and reduction values in the product sections.

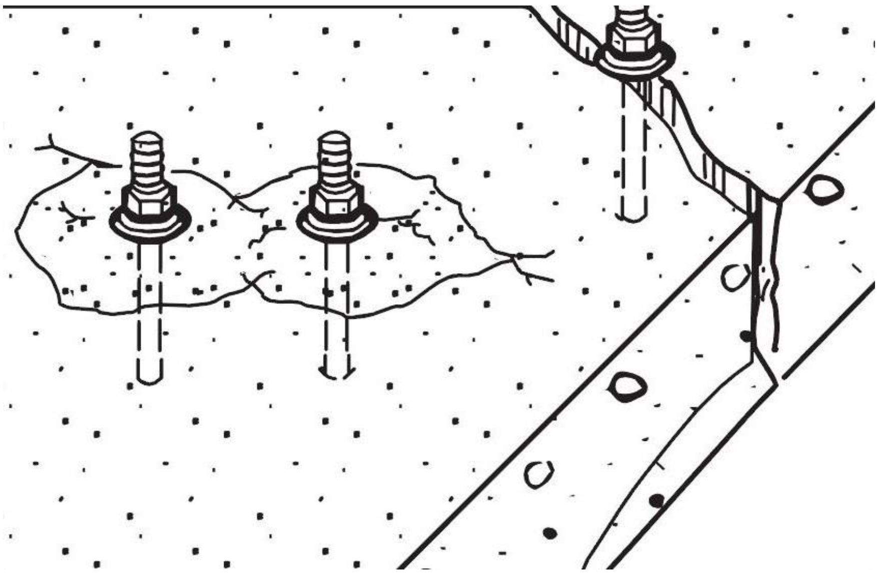


Figure 2.10: Edge Failure (AWPH, 2010)

g) Bond Failure: Shear failure of the adhesive at rod-adhesive interface or adhesive-base material interface. Occurs more commonly in deep embedment's using high strength steel rods.

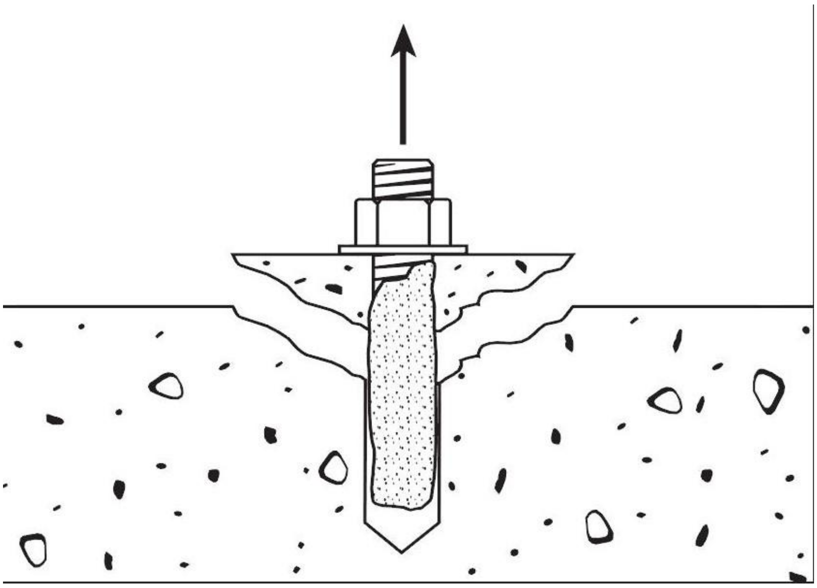


Figure 2.11: Bond Failure (AWPH, 2010)

2.2.2.2 Failure Modes Under Shear Loading

Under shear loads failure can occur either by shearing failure of the anchor steel itself or by failure of the concrete (Klingner et. al., 1982)

a) Steel Failure: Fracture of the anchor bolt occurred at the maximum force response, preceded by the crushing of the concrete in front of the anchor.

b) Concrete break-out: With small edge distance and with loading applied at right angle to the free edge, the anchor will fail in consequence of break-out of the concrete. An abrupt decrease in capacity was observed after loss of the concrete cover for the fastener (Vintzelou and Eligehausen, 1991)

2.2.2.3 Factors Affecting Failure mode in Shear

The anchor bolt diameter, the edge distance, and the embedded length are the most significant factors which influence the failure mode in shear. When compared to those, the strength of concrete and the steel are less effective on the failure modes of fasteners.

2.3 Soft Computing Techniques

An analytical model is a description of a system using mathematical concepts and language. The process of developing a mathematical model is termed mathematical modeling. Mathematical models are used not only in the natural sciences and engineering disciplines but also in the social sciences. Researchers use mathematical models most extensively. A model may help to explain a system and to study the effects of different components, and to make predictions about behavior (Wikipedia, 2008).

Artificial Intelligence (AI) techniques have been utilized as robust alternative technique for engineering analysis problems. Artificial intelligence emerged as a computers science discipline in the mid 1950s. Since then, a number of handful tools have been produced for practical use in engineering to figure out sophisticated problems which normally require human intelligence (Pham and Pham, 1999). AI can be described as the simulation of human intelligence on a machine, so that the machine effectively to identifies and uses the right part of "Knowledge" at a specified step of solving a problem. Therefore, AI alternatively might be defined as object orientation with computational models that can think and act rationally. AI has broad spectrum of research fields. It tackles various types of knowledge representation modes, different methods of intelligent search, various techniques for resolving fuzzy data and knowledge (Konar, 1999). Several AI tools that are widely utilized for engineering problems are knowledge-based systems, fuzzy logic, inductive learning, neural networks and genetic algorithms (Pham and Pham, 1999).

2.3.1 Genetic Programming

A genetic algorithm (GA) is a search technique that has been used in computing for finding precise or approximate solutions to optimization or search problems. Genetic algorithms can be categorized as global search heuristics. Genetic algorithms are a particular class of evolutionary computation. The techniques used by GA are inspired by evolutionary biology such as; inheritance, mutation, selection, crossover (recombination).

Genetic programming (GP), proposed by Koza (1992) is essentially an application of genetic algorithms to computer programs. GP has been applied successfully to solve discrete, non-differentiable, combinatory, and general nonlinear engineering optimization problems (Goldberg, 1989). It is an evolutionary algorithm based methodology inspired by biological evolution to find computer that performs a task defined by a user. Therefore, it is a machine learning technique used to construct a population of computer programs according to a fitness landscape determined by a program's ability to perform a given computational task. Similar to GA, the GP needs only the problem to be defined. Then, the program searches for a solution in a problem-independent manner (Goldberg, 1989; Zadeh, 1984).

Gene expression programming (GEP) is a natural development of genetic algorithms and genetic programming. GEP was introduced by Ferreira (2001). GEP is a natural development of GP. GEP evolves computer programs of different sizes and shapes encoded in linear chromosomes of fixed-length. GEP algorithm begins with the random generation of the fixed-length chromosomes of each individual for the initial population. Then, the chromosomes are expressed and the fitness of each individual is evaluated based on the quality of the solution it represents (Özbay et al., 2008).

GP reproduces computer programs to solve problems by executing the following steps (Fig. 2.12):

(1) Generate an initial population of random compositions of the functions and terminals of the problem (computer programs),

(2) Execute each program in the population and assign it a fitness value according to how well it solves the problem, and

(3) Create a new population of computer programs:

(i) Copy the best existing programs (reproduction),

(ii) Create new computer programs by mutation,

(iii) Create new computer programs by crossover (sexual reproduction).

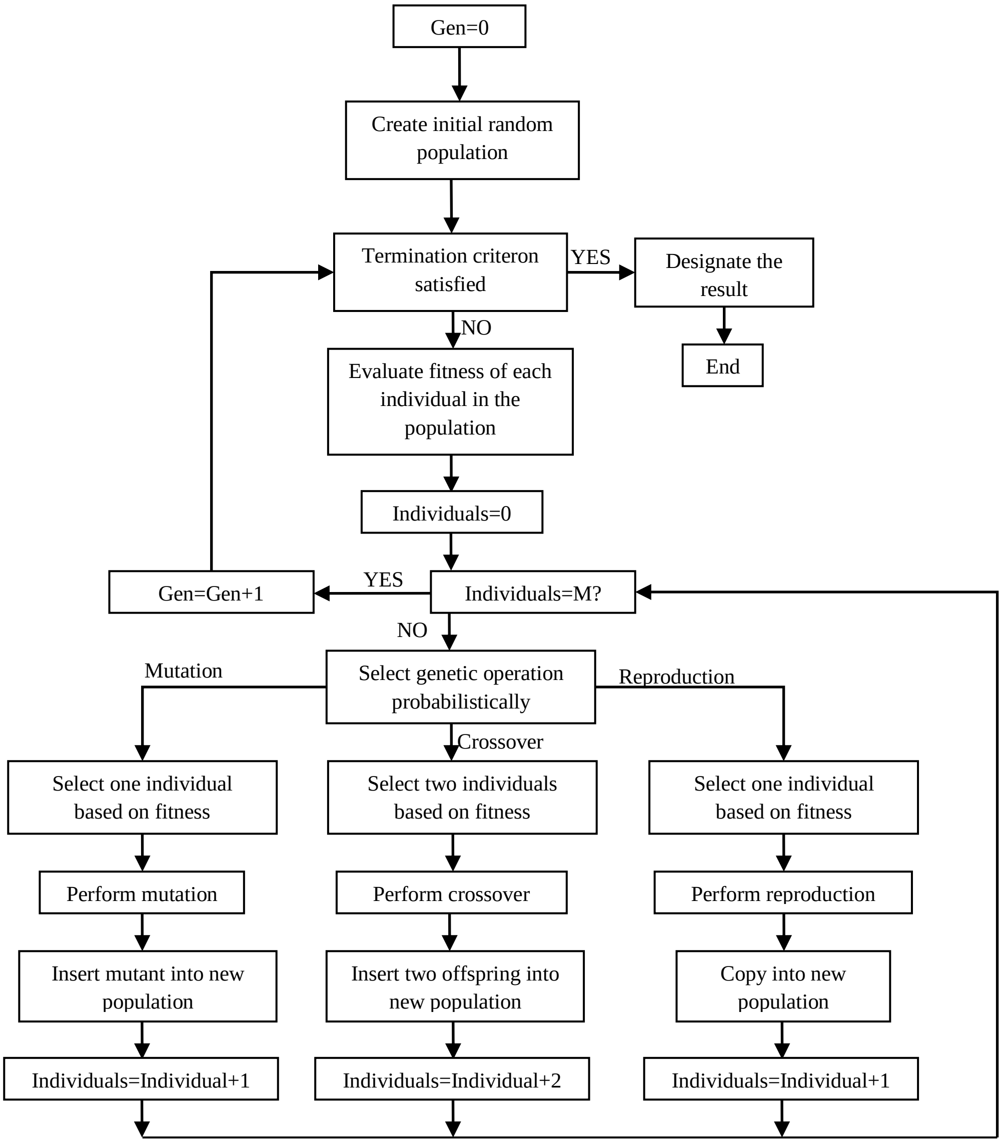


Figure 2.12 Flowchart for the genetic programming paradigm (Koza, 1992)

A significant advantage of GEP is that it makes it possible to infer exactly the phenotype given the sequence of a gene, and vice versa which is termed as Karva language. For example, the following algebraic expression (Eq 2.1) can be represented by a diagram which is the expression tree as follows (Fig. 2.12).

$$Y = \ln\left(\sqrt[3]{d_1 - \cos d_0 \times d_6}\right) \times d_2 + d_4 \qquad (2.1)$$

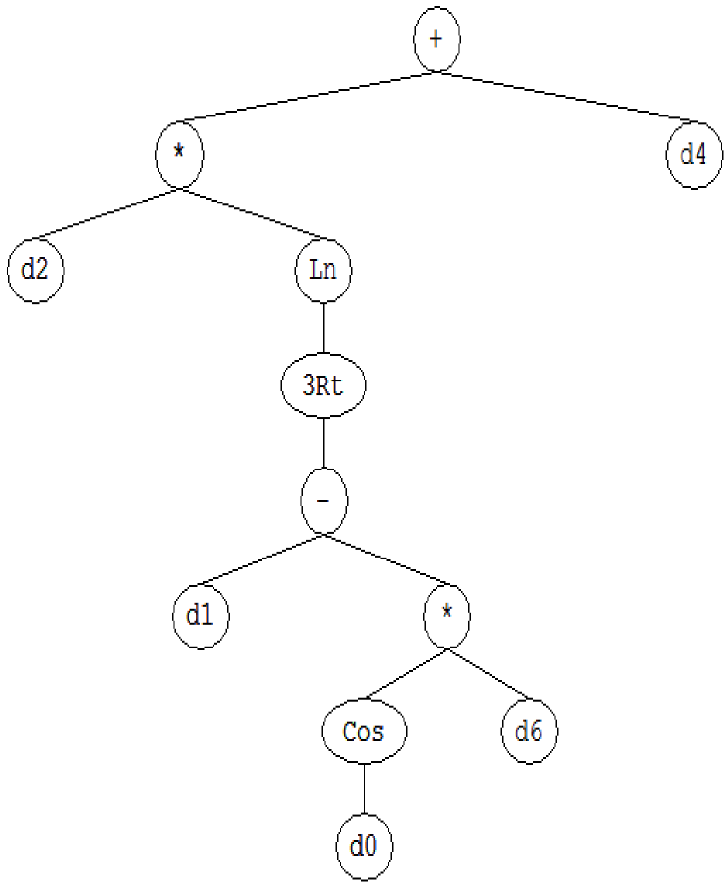


Figure 2.13 A sample sub-expression tree for a mathematical operation

CHAPTER 3

METHODOLOGY

3.1 Data Set

Table 3.1 shows various mathematical operations that are included to provide a reliable model. The parameters here are used in the formulation of the GEP model which is demonstrated in the expression tree in Figure 3.2.

Table 3.1 GEP parameters used for proposed models

P1	Function Set	+, -, *, /, √, ^, ln, exp, sin, tan
P2	Number of generation	940695
P3	Chromosomes	40
P4	Head size	10
P5	Linking function	Multiplication
P6	Number of genes	6
P7	Mutation rate	0.044
P8	Inversion rate	0.1
P9	One-point recombination rate	0.3
P10	Two-point recombination rate	0.3
P11	Gene recombination rate	0.1
P12	Gene transposition rate	0.1

3.2 Train Set

Tables 3.2 and 3.3 show the data's of train and test set such as: anchor diameter, type of anchor (threaded bar or rebar), edge distance, embedment depth, clear clearance of the anchor, type of chemical adhesive (epoxy or unsaturated polyester), method of injection of the chemical (glass capsule or cartridge injection), and compressive strength of the concrete with the experimental results of shear capacity of the anchors.

Table 3.2 Training data base used for development of the prediction model

Independent variables (X_i)								Dependent variable (Y)
X_1:Diameter (mm)	X_2:Type of injection*	X_3:Chemical type**	X_4:Anchor type***	X_5:Embedment depth (mm)	X_6:Clear clearance (mm)	X_7:fc (MPa)	X_8:Edge distance (mm)	Shear capacity (kN)
12.70	1	1	1	114	1.04	23.52	114.30	42
12.70	1	1	1	114	1.04	23.52	114.30	35
15.88	1	1	1	144	1.98	23.52	133.35	67
15.88	1	1	1	144	1.98	23.52	133.35	76
19.05	1	1	1	171	2.10	23.52	171.45	86
19.05	1	1	1	171	2.10	23.52	171.45	94
22.23	1	1	1	199	2.06	23.52	200.03	139
22.23	1	1	1	199	2.06	23.52	200.03	122
25.40	1	1	1	226	2.15	23.65	228.60	189
12.70	1	1	1	115	1.04	40.89	114.30	49
15.88	1	1	1	144	1.98	40.89	142.88	79
15.88	1	1	1	144	1.98	40.89	142.88	71
19.05	1	1	1	173	2.07	40.89	171.45	112
22.23	1	1	1	199	2.06	40.89	200.03	149
22.23	1	1	1	199	2.06	40.89	200.03	138
9.53	1	1	1	86	1.08	23.52	38.10	6
9.53	1	1	1	86	1.08	23.52	38.10	6
15.88	1	1	1	86	1.98	23.65	63.50	16
15.88	1	1	1	86	1.98	23.65	63.50	15
9.53	1	1	1	86	0.79	13.48	85.73	19
12.70	1	1	1	114	0.79	13.48	85.73	36
12.70	1	1	1	117	0.79	13.48	85.73	42
15.88	1	1	1	117	1.59	13.48	142.88	60
15.88	1	1	1	117	1.59	13.48	142.88	57
19.05	1	1	1	169	1.59	13.48	171.45	64
19.05	1	1	1	168	1.59	13.48	171.45	65
19.05	1	1	1	175	1.59	13.48	171.45	72
19.05	1	1	1	173	1.59	13.48	171.45	72
22.23	1	1	1	201	4.76	13.48	200.03	103
25.40	1	1	1	225	1.59	13.28	228.60	107
25.40	1	1	1	230	1.59	13.28	228.60	114
12.70	0	1	0	113	1.59	31.57	107.95	54
15.88	0	1	0	133	1.59	31.57	127.00	69
15.88	0	1	0	135	1.59	31.57	127.00	57
19.05	0	1	0	178	1.59	31.57	155.58	87

Table 3.2.i (continued)

Independent variables (X_i)								Dependent variable (Y)
X_1:Diameter (mm)	X_2:Type of injection*	X_3:Chemical type**	X_4:Anchor type***	X_5:Embedment depth (mm)	X_6:Clear clearance (mm)	X_7:fc (MPa)	X_8:Edge distance (mm)	Shear capacity (kN)
19.05	0	1	0	168	1.59	31.57	155.58	90
22.23	0	1	0	164	3.18	31.57	168.28	120
22.23	0	1	0	165	3.18	31.57	168.28	100
25.40	0	1	0	210	3.18	31.57	203.20	145
25.40	0	1	0	208	3.18	31.57	203.20	151
12.70	0	1	0	103	1.59	13.13	107.95	38
12.70	0	1	0	114	1.59	13.13	107.95	38
15.88	0	1	0	133	1.59	13.13	127.00	44
15.88	0	1	0	127	1.59	13.13	127.00	49
19.05	0	1	0	162	1.59	13.13	171.45	78
19.05	0	1	0	175	1.59	13.13	171.45	65
22.23	0	1	0	165	3.18	13.34	177.80	75
22.23	0	1	0	175	3.18	13.34	177.80	87
25.40	0	1	0	203	3.18	13.34	203.20	126
25.40	0	1	0	187	3.18	13.34	203.20	103
8.00	0	0	1	80	1.00	15.00	40.00	9
8.00	0	0	1	80	1.00	43.00	40.00	12
10.00	0	0	1	90	1.00	43.00	45.00	17
12.00	0	0	1	110	1.00	15.00	55.00	19
16.00	0	0	1	125	1.00	16.00	62.50	24
16.00	0	0	1	125	1.00	16.00	125.00	53
20.00	0	0	1	170	2.50	16.00	85.00	44
20.00	0	0	1	170	2.50	16.00	170.00	70
24.00	0	0	1	210	2.00	16.00	262.50	115
24.00	0	0	1	210	2.00	28.00	105.00	62
12.00	0	0	1	110	1.00	14.00	55.00	45
12.00	0	0	1	110	1.00	14.00	165.00	68
12.00	0	0	1	110	1.00	36.00	110.00	106
12.00	0	0	1	110	1.00	36.00	137.50	106

*1 for cartridge injection, 0 for glass capsule **1 for epoxy and 0 for unsaturated polyester ***1 for steel rebar, 0 for threaded bars

Table 3.3 Testing data base used for evaluating the performance of the prediction model

Independent variables (X_i)								Dependent variable (Y)
X_1:Diameter (mm)	X_2:Type of injection*	X_3:Chemical type**	X_4:Anchor type***	X_5:Embedment depth (mm)	X_6:Clear clearance (mm)	X_7:fc (MPa)	X_8:Edge distance (mm)	Shear capacity (kN)
9.53	1	1	1	85.73	1.08	23.52	85.73	26
12.70	1	1	1	114.30	1.04	23.52	114.30	41
15.88	1	1	1	143.94	1.98	23.52	133.35	77
19.05	1	1	1	171.45	2.10	23.52	171.45	91
25.40	1	1	1	226.49	2.15	23.65	228.60	170
25.40	1	1	1	226.49	2.15	23.65	228.60	149
15.88	1	1	1	143.94	1.98	40.89	142.88	78
19.05	1	1	1	172.52	2.07	40.89	171.45	105
9.53	1	1	1	85.73	1.08	23.52	38.10	8
15.88	1	1	1	85.73	1.98	23.65	63.50	16
12.70	1	1	1	117.37	0.79	13.48	85.73	41
15.88	1	1	1	114.33	1.59	13.48	142.88	59
19.05	1	1	1	170.92	1.59	13.48	171.45	83
22.23	1	1	1	206.45	4.76	13.48	200.03	93
22.23	1	1	1	200.05	4.76	13.48	200.03	92
25.40	1	1	1	226.70	1.59	13.28	228.60	116
15.88	0	1	0	133.35	1.59	31.57	127.00	71
19.05	0	1	0	168.28	1.59	31.57	155.58	96
22.23	0	1	0	168.28	3.18	31.57	168.28	128
25.40	0	1	0	206.38	3.18	31.57	203.20	126
12.70	0	1	0	106.38	1.59	13.13	107.95	41
15.88	0	1	0	142.88	1.59	13.13	127.00	48
19.05	0	1	0	155.58	1.59	13.13	171.45	78
22.23	0	1	0	177.80	3.18	13.34	177.80	83
25.40	0	1	0	177.80	3.18	13.34	203.20	98
10.00	0	0	1	90.00	1.00	15.00	45.00	14
10.00	0	0	1	90.00	1.00	15.00	67.50	19
12.00	0	0	1	110.00	1.00	43.00	55.00	27
16.00	0	0	1	125.00	1.00	36.00	62.50	37
20.00	0	0	1	170.00	2.50	36.00	85.00	63
24.00	0	0	1	210.00	2.00	16.00	105.00	51
12.00	0	0	1	110.00	1.00	14.00	110.00	57
12.00	0	0	1	110.00	1.00	38.00	55.00	60
12.00	0	0	1	110.00	1.00	38.00	110.00	91

3.3 Construction of Model

The anchor's adhesive layer bears on the concrete, when is loaded in shear. Due to enough force this will cause the edge of the concrete to break out. Figure 3.1 shows a typical edge breakout failure of a single adhesive anchor. The models given in the design codes basically depend on the compressive strength of the concrete and edge distance. Some models also consider embedment depth and diameter of the anchor bolt. However, clearance distance (see Fig. 3.1), type of the anchor, type of adhesive and method of injection have not yet been considered in the formulation of shear capacity of the anchor. For this, anchor diameter, type of anchor (threaded bar or rebar), edge distance, embedment depth, clear clearance of the anchor, type of chemical adhesive (epoxy or unsaturated polyester), method of injection of the chemical (glass capsule or cartridge injection), and compressive strength of the concrete with the experimental results of shear capacity of the anchors were arranged to obtain a data set. The data set were randomly divided into two groups to be used as test and train in Tables 3.2 and 3.3, respectively. GeneXproTools.4.0 software was employed in deriving the mathematical model presented in Eqn 9.

The models developed by GEP in its native language can be automatically parsed into visually appealing expression trees, permitting a quicker and more complete comprehension of their mathematical/logical intricacies. Figure 3.2 demonstrates the expression tree for the terms used in the formulation of the GEP model which has the parameters given in Table 3.1.

$$V_U = V_1 \times V_2 \times V_3 \times V_4 \times V_5 \times V_6 \qquad \text{(Eqn 3.1)}$$

$$V_1 = \left[\ln\left(\sqrt[3]{-6.227142 + X_8 - X_3 - X_5 + \tan(X_1^4)}\right)\right]^2 \qquad \text{(Eqn 3.1a)}$$

$$V_2 = \ln\left[\sqrt[3]{(\sqrt{X_7^2 + X_1})^{\sin^2(X_7)} + X_1}\right] \qquad \text{(Eqn 3.1b)}$$

$$V_3 = \ln\left[X_7 - \sin^3(X_5 + 3.883179) + \tan(-7.08139 * X_5\right] \qquad \text{(Eqn 3.1c)}$$

$$V_4 = \sqrt[6]{X_7 + X_6 \times (\tan(\sin X_7) - X_4 + 5.801483)} \qquad \text{(Eqn 3.1d)}$$

$$V_5 = \ln[\ln(X_1 - \tan(X_8 + 8.091003 - X_4) - \tan(5.138702 \times X_1))] \qquad \text{(Eqn 3.1e)}$$

$$V_6 = \left[\ln\left(\sqrt[3]{\tan(\ln X_8) + (-6.909272)^{X_2} + X_8 + X_4}\right)\right]^3 \qquad \text{Eqn 3.1f)}$$

Where V_u is the ultimate shear capacity of adhesive anchor in uncracked concrete (kN); X_1: Anchor diameter (mm); X_2: Injection type (1 for cartridge injection, 0 for glass capsule); X_3:Chemical type (1 for epoxy and 0 for unsaturated polyester); X_4:Type of anchor (1 for steel rebar, 0 for threaded bars); X_5:Embedment depth (mm); X_6: Clear clearance (mm), X_7:Concrete compressive strength (MPa), and X_8: Edge distance (mm).

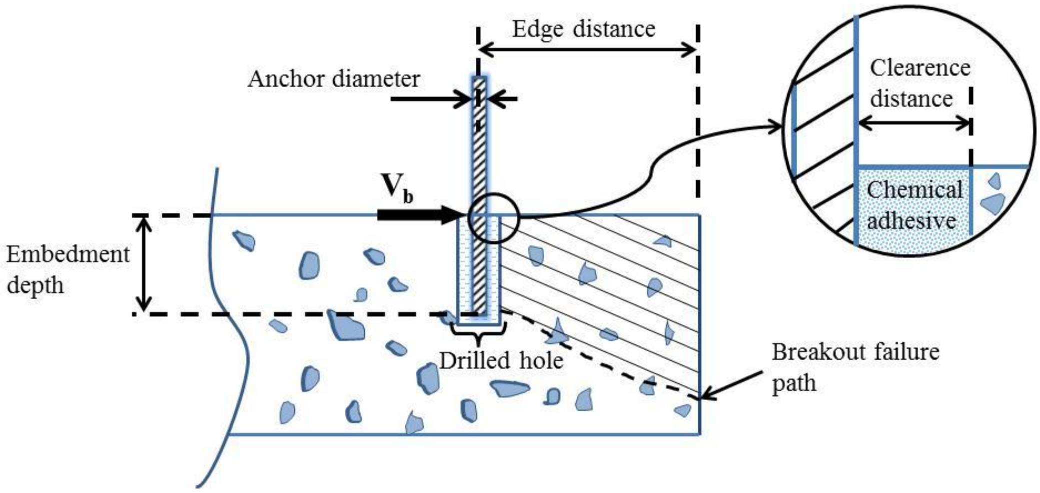
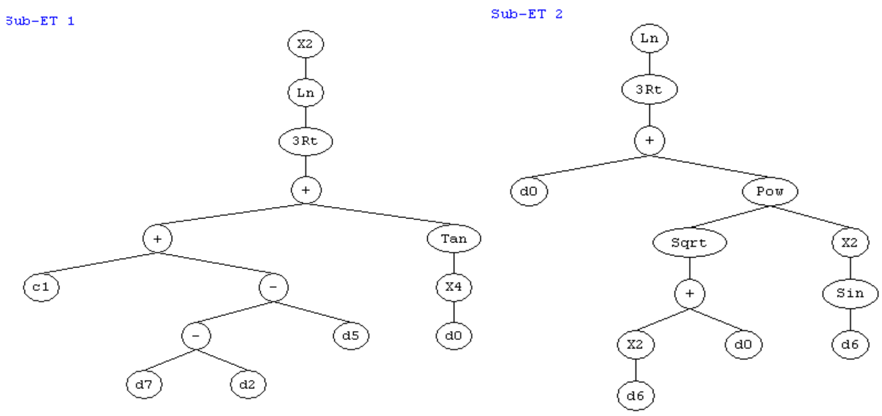


Figure 3.1 Schematic presentation of typical post installed single adhesive anchor under shear loading



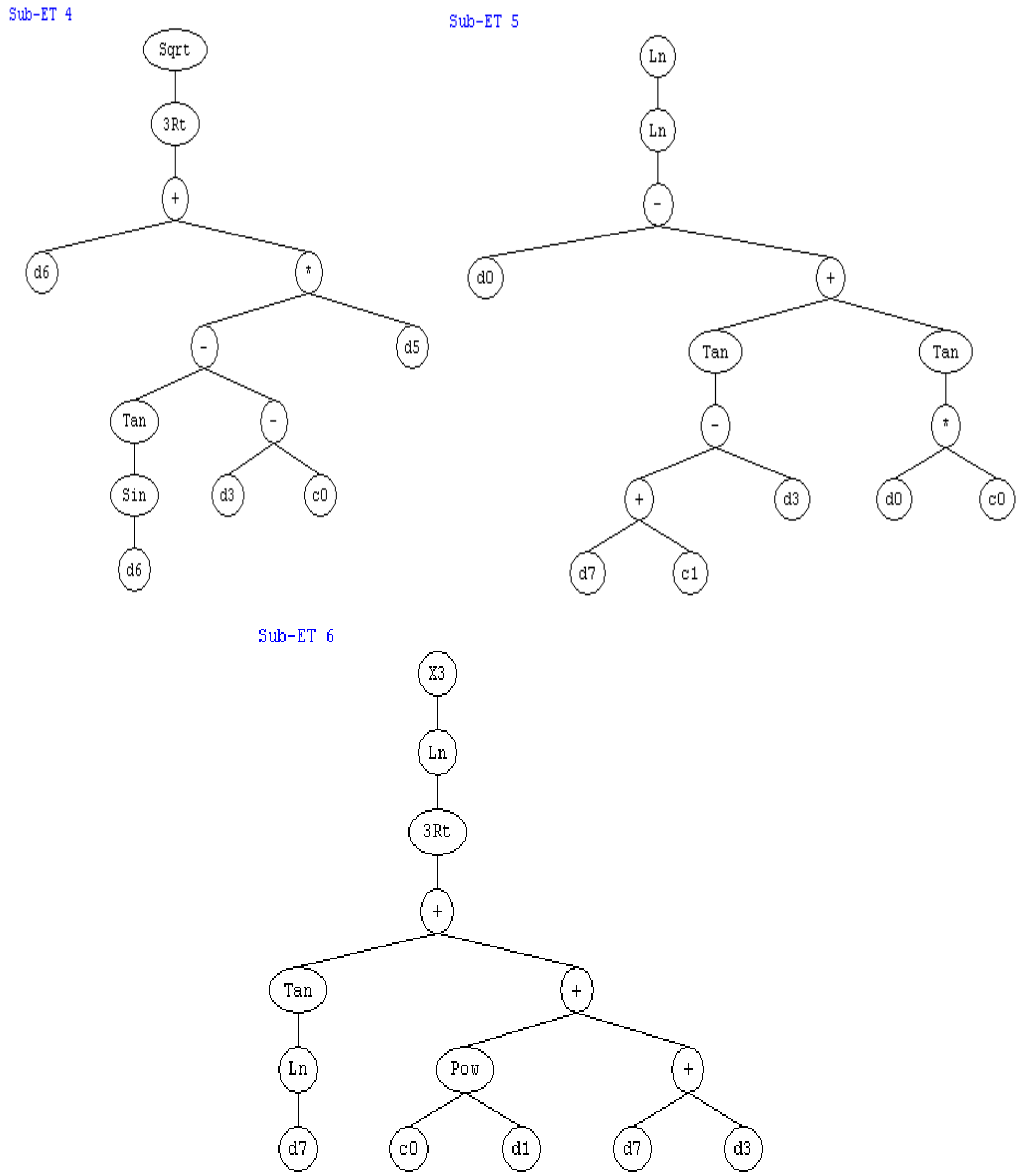


Figure 3.2 Expression tree for GEP model [d_0: Anchor diameter (mm), d_1: Injection type (1 for cartridge injection, 0 for glass capsule), d_2:Chemical type (1 for epoxy and 0 for unsaturated polyester), d_3:Type of anchor (1 for steel rebar, 0 for threaded bars), d_4:Embedment depth (mm), d_5: Clear clearance (mm), d_6:Concrete compressive strength (MPa), d_7: Edge distance (mm) c_0 and c_1: constants (c_0=-7.08139 for Sub-ET3, c_0=5.801483 for Sub-ET4, c_0=5.138702 for Sub-ET5, c_0=-6.909272 for Sub-ET6, c_1=-6.227142 for Sub-ET1, c_1=3.883179 for Sub-ET3, c_1=8.091003 for Sub-ET5)]

CHAPTER 4

AVAILABLE FORMULATIONS

4.1 Estimating shear capacity of anchors in current design codes

In order to estimate the concrete edge breakout strength of anchor bolts under shear loading various relations have been proposed in the literature as given in Eqns 4.1 through 4.8

Bickel and Shaik 2002

Hofman et al., 2004

Ueda et al., 1990

ACI Committee 1997

ACI Committee 2007

ACI Committee 2008

Fuchs et al 1995

PCI 1998 The ACI shear resistance formula assumes the concrete failure surface to be a semi cone of height equal to edge distance and a contact inclination angle of 45^o with respect to the contact edge (Ueda et al., 1990) The shear resistance of anchor bolt is calculated on the basis of the tensile strength of the concrete acting over the projected area of the semi-cone surface. According to ACI 349-97 (ACI 1997)

The design shear strength is given by the formula below (Eqn 4.1 in U.S. customary units). (Ueda et al., 1990) presented the same relation in SI units (Eqn 4.2). The concrete capacity design method is based on K-method developed by University of Stuttgart (Germany) in the late 1980s (Bickel and Shaik, 2002) For ACI 349-06 (ACI, 2007) the value of k = 7 was valid for cracked concrete while the tests selected herein were performed in uncracked concrete. Assuming a ratio of uncracked to cracked strength of 1.4, a value k = 9.8 (k = 7 × 1.4) was utilized for the evaluation of predicted capacities (Lee et al., 2010) In ACI 349-06, edge breakout shear capacity of bolt was presented by Eqn 4.3 (ACI 2007) The models based on concrete capacity design (CCD) (ACI 2008)

(Fuchs et al., 1995**)** and Modified CCD (Hofmann et al., 2004) were given in Eqns 4.4-4.6. The capacity of a single anchor in uncracked structural member under shear loading toward the free edge is also described in Precast/Prestressed Concrete Institute (PCI) Design Handbook (fifth edition) (PCI 1998) Eqns 4.7 and 4.8 of PCI method are given in US customary and SI units below.

ACI 349-97 (in U.S. customary units) (ACI 1997)

$$V_U = 2\pi c_1^2 \sqrt{f'_c} \quad \text{(Lb)} \qquad \text{(Eqn 4.1)}$$

SI equivalent of this formula (Ueda et al., 1990):

$$V_U = 0.522 c_1^2 \sqrt{f'_c} \quad \text{(N)} \qquad \text{(Eqn 4.2)}$$

ACI 349-06 (in U.S. customary units) (ACI 2007):

$$V_U = 9.8(l/d_0)^{0.2} \sqrt{d_0} \sqrt{f'_c}\, c_1^{1.5} \quad \text{(Lb)} \qquad \text{(Eqn 4.3)}$$

Concrete Capacity Design (CCD method) (in U.S. customary units) (ACI 2008):

(Fuchs et al., 1995):

$$V_U = 13(l/d_0)^{0.2} \sqrt{d_0} \sqrt{f'_c}\, c_1^{1.5} \quad \text{(Lb)} \qquad \text{(Eqn 4.4)}$$

SI equivalent of this formula (Bickel & Shaik 2002)**:**

$$V_U = 1.1(l/d_0)^{0.2} \sqrt{d_0} \sqrt{f'_{cc}}\, c_1^{1.5} \quad \text{(N)} \qquad \text{(Eqn 4.5)}$$

Modified CCD method (in SI units) (Hofman et al., 2004):

$$V_U = 3 d_0^{0.1(h_{ef}/c_1)} h_{ef}^{0.1(d_0/c_1)^{0.2}} \sqrt{f'_{cc}}\, c_1^{1.5} \quad \text{(N)} \qquad \text{(Eqn 4.6)}$$

PCI method (in U.S. customary units) (PCI 1998):

$$V_U = 12.5 c_1^{1.5} \sqrt{f'_c} \quad \text{(Lb)} \qquad \text{(Eqn 4.7)}$$

SI equivalent of this formula (PCI 1998):

$$V_U = 5.2 c_1^{1.5} \sqrt{f'_c} \quad \text{(N)} \qquad \text{(Eqn 4.8)}$$

Where V_u is the ultimate shear capacity of an adhesive anchor in uncracked concrete (lb for the Eqns in U.S. customary units N for the Eqns in S.I. unit); f_c' is concrete compressive strength (psi for the Eqns in U.S. customary units MPa for the Eqns in S.I. unit) to be verified using cylinders; f_{cc}' is concrete compressive strength (MPa) to be verified using 200 mm cubes; h_{ef} is embedment depth (mm); d_o is diameter of anchor (in. for the Eqns in U.S. customary units mm for the Eqns in S.I. unit); l is load bearing length of anchor (in. for the Eqns in U.S. customary units mm for the Eqns in S.I. unit); and c_1 is anchor edge distance (in. for the Eqns in U.S. customary units mm for the Eqns in S.I. unit).

CHAPTER 5

RESULTS AND DISCUSSIONS

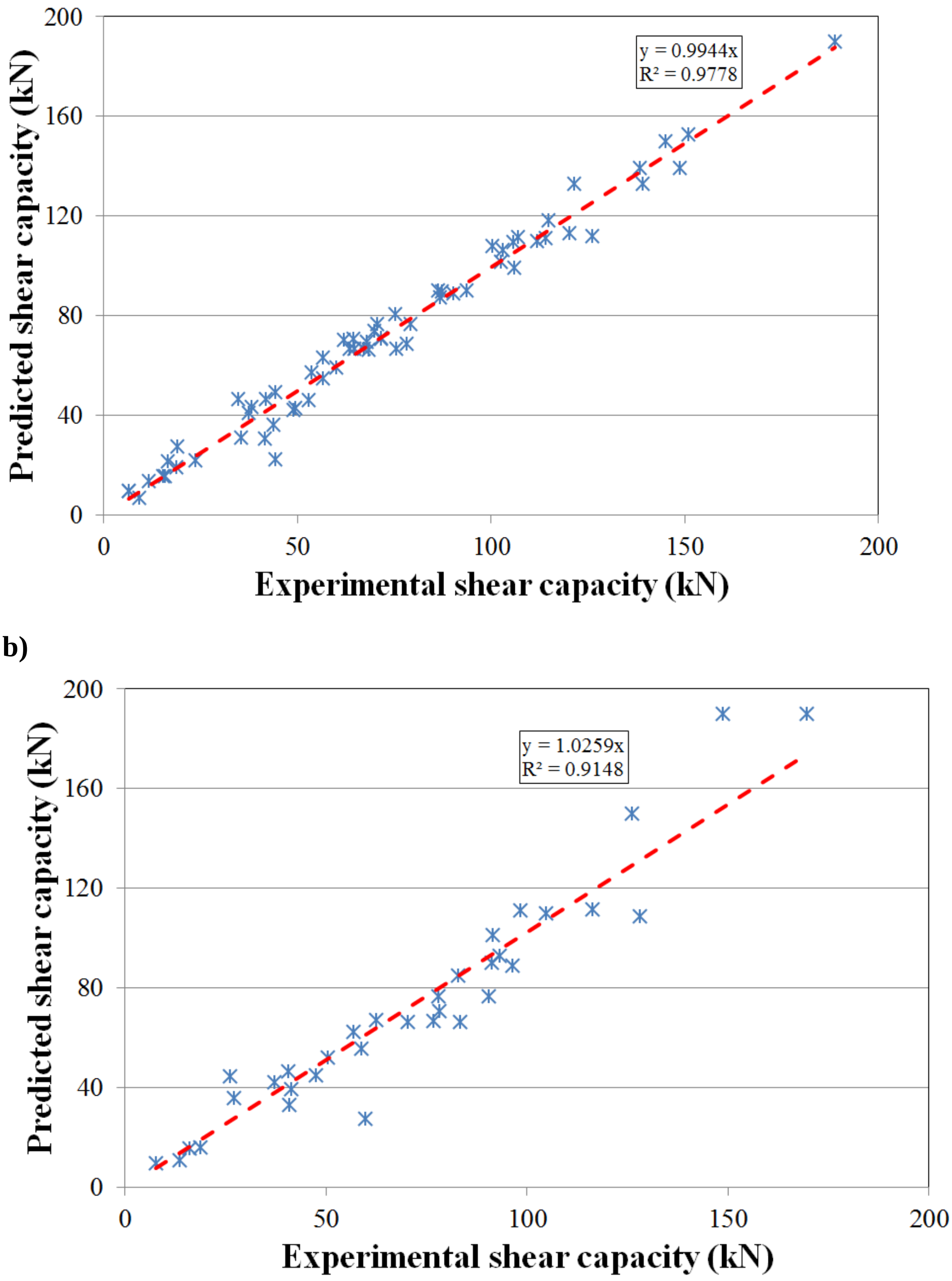
5.1 Performance of Model

Performance of the proposed GEP prediction model in Eqn. 3.1 was depicted in Figure 5.1 for both train and testing data sets. Moreover, the correlations between experimental and predicted shear capacities for the existing models were also given in Figures 5.2-5.6 for the entire data. Figure 5.1 revealed that high estimation accuracy was accomplished for both training and testing data sets. The correlation coefficient of training set was 0.98 while that of testing was 0.92. It is seen in Figure 5.4 that despite having lower R^2 value, CCD method presented similar trend as GEP model. As a result of uniform scatter of the data, the correlation coefficients calculated for the other models also appeared to be very close to each other. However, the shear capacities computed from ACI 349-97, ACI 349-06, and PCI models under-predicted the actual values while Modified CCD method provided over-prediction. Some statistical parameters were also given in Table 3.1 for comparing the tendency of the distribution of the predicted values**.** Of all the existing formulas, CCD method appeared to be the most reliable one attributed to its relatively lower prediction error.

Figure 5.7 showed that the normalized values tend to approach to almost 1 for the compressive strengths of 24 to 32 MPa whereas beyond that a divergence was obtained. Tendency of clustering the data was observed for the highest edge distance in Figure 5.8 for the highest diameter in Figure 5.9, and for the highest embedment depth in Figure 5.10. In the study of Gesoğlu and Güneyisi prediction models were developed to estimate the pullout capacity of adhesive anchors through soft computing methods. They also reported that the prediction capability of the proposed models and the CCD method were increased for deeper embedment depth and larger diameter anchors.

At the same time, Figures 5.7 through 5.10 indicate the variations of the normalized shear capacity found by dividing the predicted over experimental values, versus compressive strength of the concrete, edge distance, diameter of anchor and embedment depth of the anchor, respectively. Since compressive strength of the concrete and edge distance are the fundamental factors as being available in all of the prediction models, Figures 5.7 and 5.8 contained all of the prediction models dealt with this study. Nevertheless, in Figures 5.9 and 5.10, ACI 349-97 and PCI formulas are excluded because they do not include the diameter and embedment depth of the anchor (Eqns 4.2 and 4.8). It can be seen from the figures that CCD method and proposed GEP model revealed a very close trend in terms of prediction performance. For example, considering the overall 98 normalized values, 60 points for GEP model and 38 points for CCD model fell between ±10% limits while 10, 5, 3 and only 1, point were observed for ACI 349-97, modified CCD, PCI, and ACI 349-06 models, respectively. Modified CCD model gave the highest normalized values for all of the factors considered. The range of the normalized values for modified CCD model was observed to be 0.50-2.67. However, the range for the proposed GEP model was 0.45-1.69. The lowest upper limit for the normalized values was observed for both ACI 349-06 and PCI models as 0.91. As seen in Figures 5.7-5.8, these two models exhibited similar trend in under predicting the shear capacities for a given compressive strength and edge distance.

a)



b)

Figure 5.1 Performance of the proposed GEP model: a) train set and b) test set

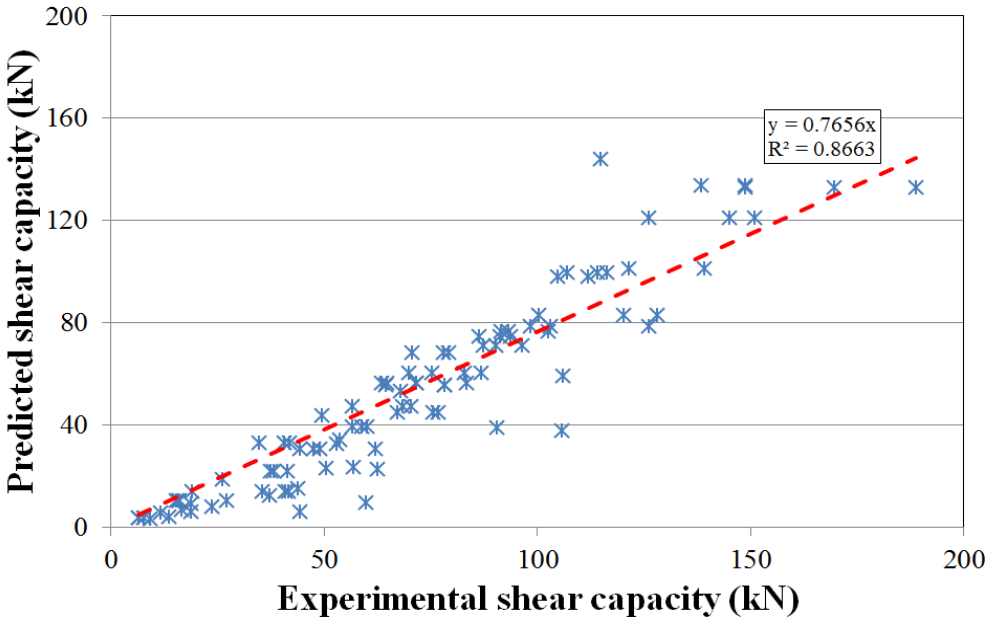


Figure 5.2 Predicted shear capacity values from ACI 349-97

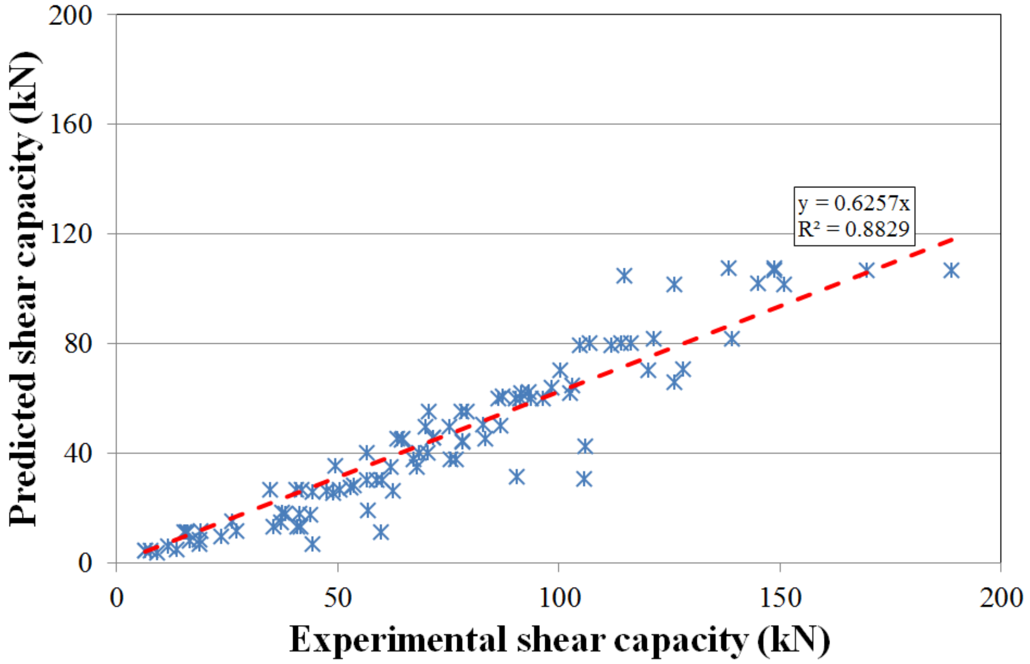


Figure 5.3 Predicted shear capacity values from ACI 349-06

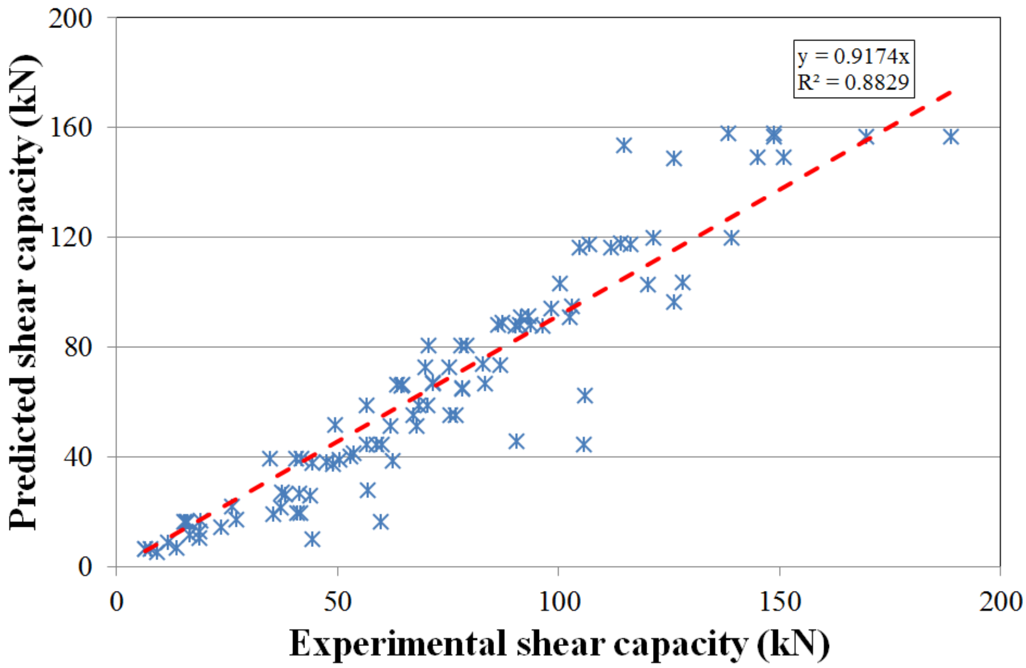


Figure 5.4 Predicted shear capacity values from CCD method

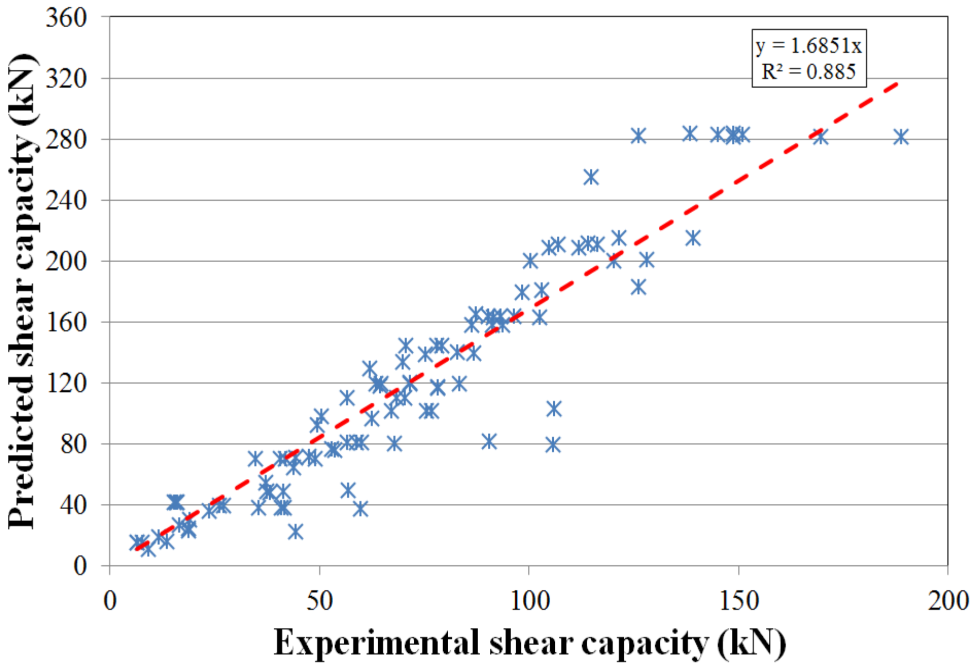


Figure 5.5 Predicted shear capacity values from modified CCD method

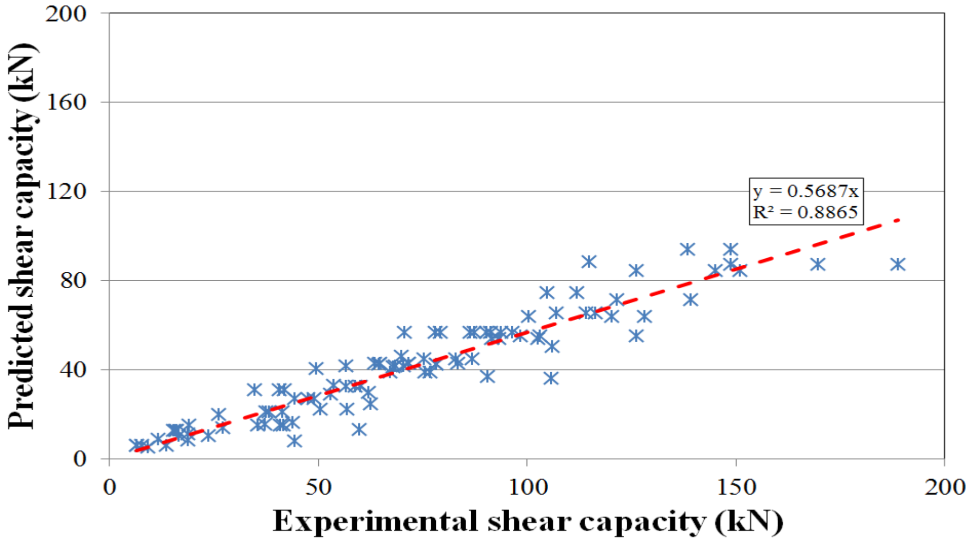


Figure 5.6 Predicted shear capacity values from PCI method

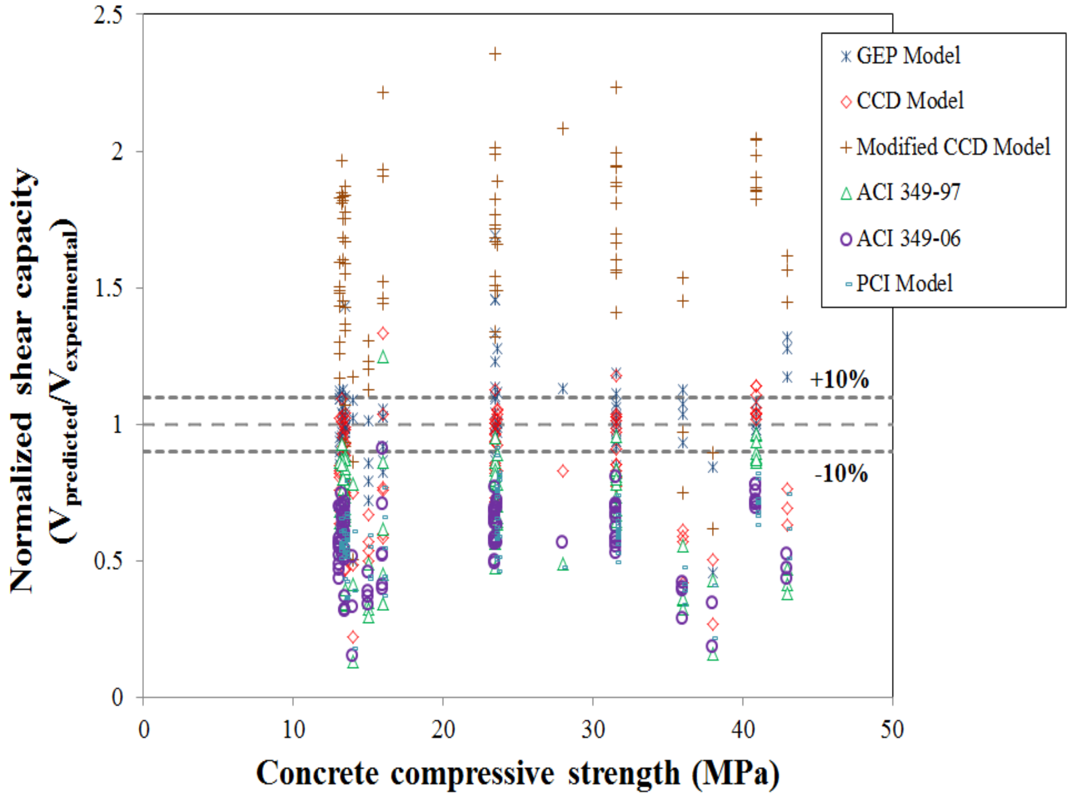


Figure 5.7 Prediction performance of the GEP, CCD, modified CCD, ACI 349-97, ACI 349-06, and PCI models for different concrete compressive strengths

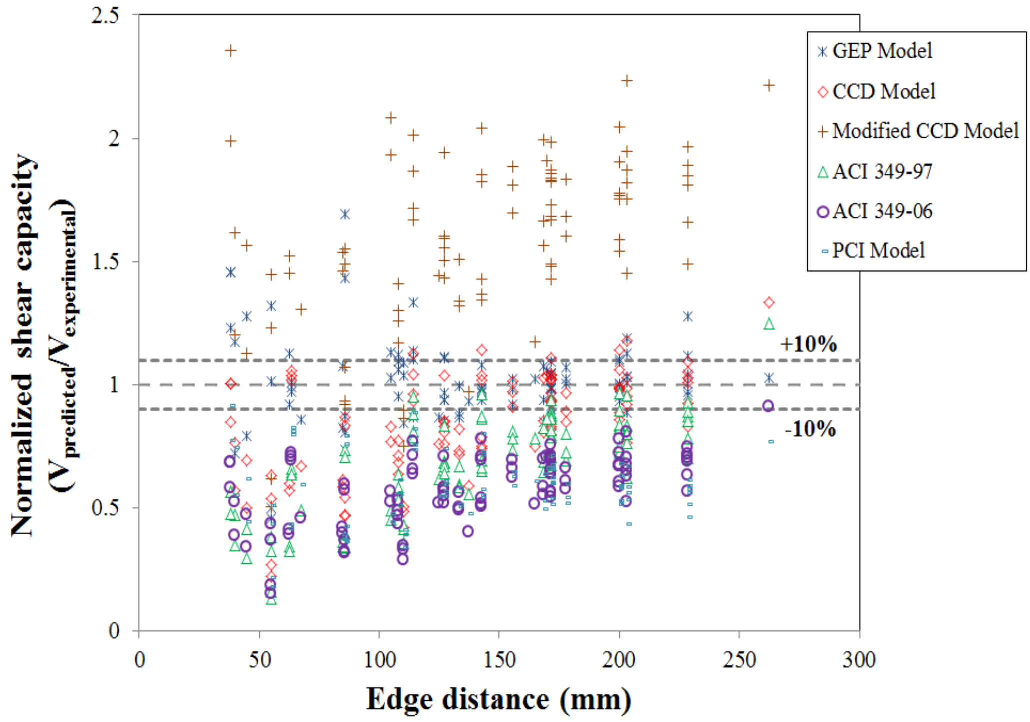


Figure 5.8 Prediction performance of the GEP, CCD, modified CCD, ACI 349-97, ACI 349-06, and PCI models for different edge distances

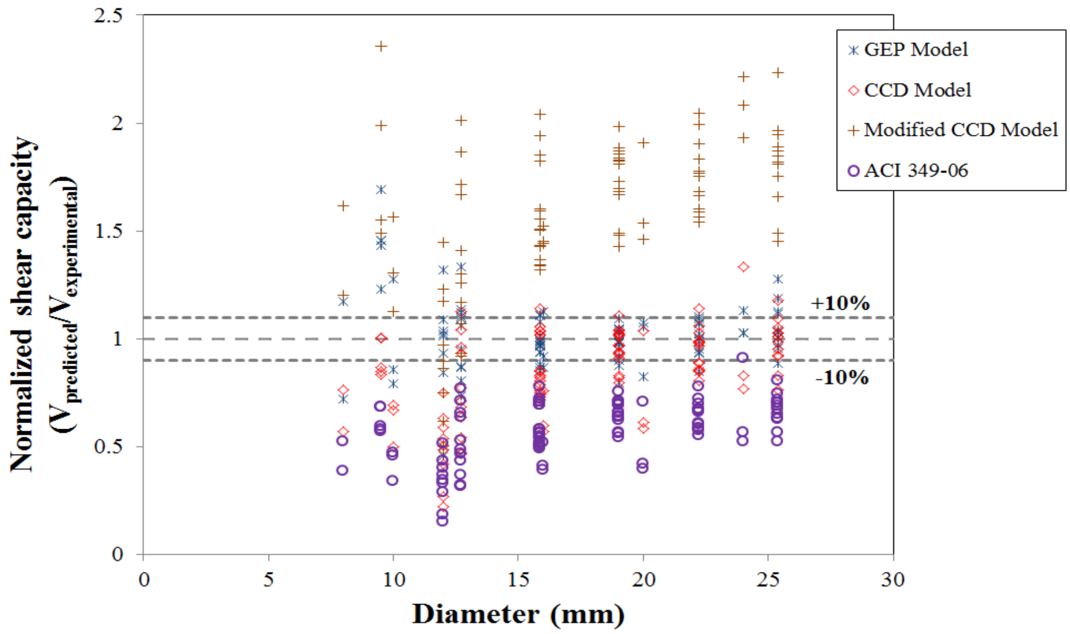


Figure 5.9 Prediction performance of the GEP, CCD, modified CCD, and ACI 349-06 models for different anchor diameters

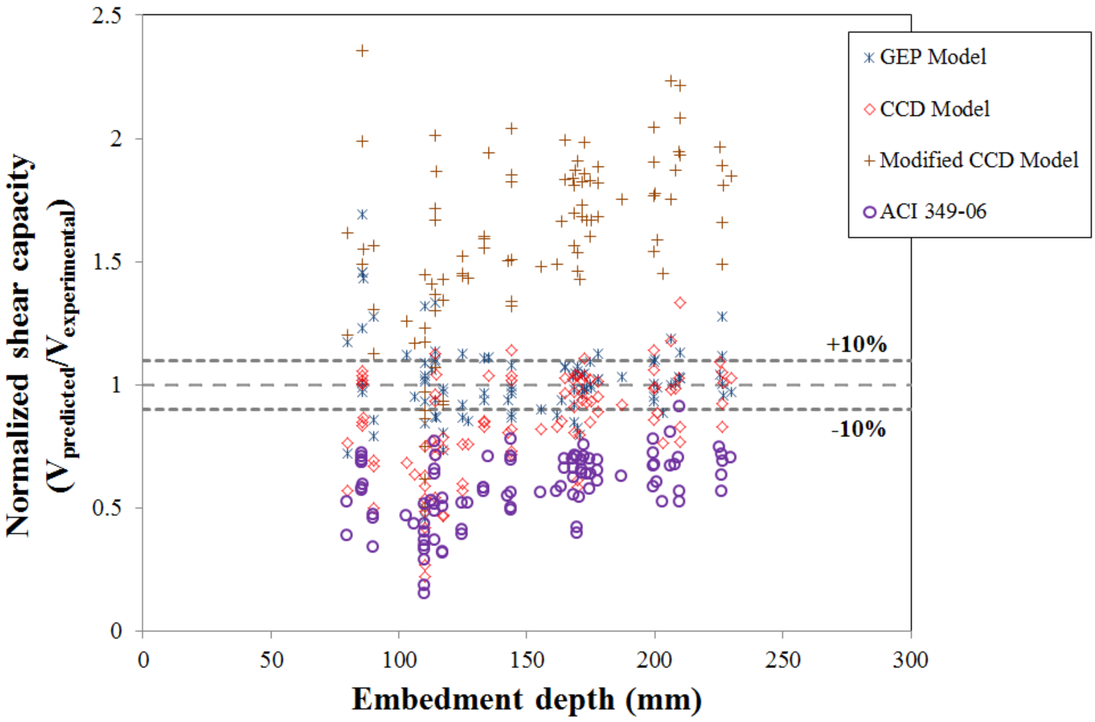


Figure 5.10 Prediction performance of the GEP, CCD, modified CCD, and ACI 349-06 models for different embedment depths

5.2 Statistical analysis of the results

The performance of all models was evaluated by using the some statistical parameters. The quality of the prediction can normally be characterized by the mean square error (MSE) of the predicted values from the real measured data. The smaller the MSE of the both data sets (train and test) is the higher is the predictive quality. Mean absolute error (MSE), mean absolute percentage error (MAPE), and root mean square error (RMSE) have been introduced to examine the performance of the models. Statistical formulations of these parameters are given in Eqns. 5.1 through 5.3. Lower MAE and MAPE values also show the robustness of the proposed models.

$$MSE = \frac{\sum_{i=1}^{n}(m_i - p_i)^2}{n} \tag{5.1}$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{m_i - p_i}{m_i}\right| \times 100 \tag{5.2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(m_i - p_i)^2}{n}} \tag{5.3}$$

where m’ and p’ are mean values of measured (m_i) and predicted (p_i) values, respectively.

Table 5.1 includes some statistical parameters for comparing the tendency of the distribution of the predicted values. The proposed GEP model has the lowest errors such that MAPE (mean absolute percentage error) is about 10 and 14% for the train and test sets, respectively. However, when the existing models in the literature are considered, MAPE ranged from 19% to 66%, depending on the prediction capability of the model. Therefore, this absolute error of the proposed GEP model seemed to be fairly reasonable when the noisy nature of the experimental results of adhesive anchors are taken into account (Sakla 2003) (Gesoğlu and Güneyisi 2007)

Table 5.1 Statistical parameters of the proposed model as well as existing one

Parameters	GEP model		CCD model	Modified CCD model	ACI 349-97	ACI 349-06	PCI model
	Training data set	Testing data set					
Mean Square Error (MSE)	36.9	168.7	261.3	3858.9	556.7	1051.5	1327.6
Mean Absolute Percent Error (MAPE)	10.0	14.2	18.9	66.0	33.0	42.2	41.5
Root Mean Square Error (RMSE)	6.1	13.0	16.2	62.1	23.6	32.4	36.4
Correlation Coefficient (R^2)	0.98	0.92	0.88	0.89	0.87	0.88	0.89

CHAPTER 6

CONCLUSIONS

Based on the analyses presented above, the following conclusions may be drawn:

Breakout shear capacity prediction model was developed by genetic programming considering the chemical characteristics and method of the placing of the adhesive anchors. The model provided reasonable predicted values with significantly high accuracy. The empirical formulation was generated through gene expression programming (GEP) with correlation coefficient of 0.98.

Although the database for testing were not utilized for training, a high level of estimation was obtained for both training and testing data sets associated with low mean absolute percentage of error and high coefficients of correlation. This indicates the generalization capability of the developed model.

The proposed model was compared with the existing formulas available in ACI 349-97, ACI 349-06, and ACI 318-08 (CCD method), PCI-98 design handbook as well as the model proposed by Hoffman, (2004) namely, modified CCD method. The statistical analysis revealed that the proposed GEP model had relatively lower errors than the others. The closest prediction tendency to the GEP model was demonstrated by CCD method. Normalization of the predicted values was performed to evaluate the performance of the existing and proposed prediction models. It was observed that ACI 349-97, ACI 349-06, PCI method, and CCD method under predicted while modified CCD method over predicted the shear capacity. The values obtained from

PCI model, ACI 349-97 and ACI 349-06 models appeared to be close to each other. However, the values obtained from GEP model were observed to be more uniform and much closer to the actual results.

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