JUNE 2017

M.Sc. in Civil Engineering

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UNIVERSITY OF GAZIANTEP

GRADUATE SCHOOL OF

NATURAL & APPLIED SCIENCES

NONLINEAR FINITE ELEMENT MODELING OF POST TENSIONED CANTILEVER CONCRETE BEAMS USING DIFFERENT TENDON PROFILES

M. SC. THESIS

IN

CIVIL ENGINEERING

BY

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JUNE 2017

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M.Sc. Thesis

in

Civil Engineering

University of Gaziantep

Supervisor

Assoc. Prof. Dr. Nildem TAYŞİ

by

Awat Hassan FAQE NABI

June 2017

REPUBLIC OF TURKEY
UNIVERSITY OF GAZİANTEP
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES
CIVIL ENGINEERING DEPARTMENT

Name of the thesis: Nonlinear Finite Element Modeling of Post Tension Concrete Cantilever Beams Using Different Tendon Profiles

Name of the student: Awat Hassan FAQE NABI

Exam date: 09.06.2017

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This is to certify that we have read this thesis and that in our consensus opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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Awat Hassan FAQE NABI

ABSTRACT

NONLINEAR FINITE ELEMENT MODELING OF POST TENSION CONCRETE CANTILEVER BEAMS USING DIFFERENT TENDON PROFILES

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M.Sc. in Civil Engineering
Supervisor: Assoc. Prof. Dr. Nildem TAYŞİ
June 2017
59 pages

Prestressing is widely used technic all over the world for constructions of buildings, bridges, towers, offshore structures etc. due to its efficiency and economy for achieving requirements the long span with small depth. It is used for flexural strengthening of reinforced concrete structures for improving cracking loads and decreasing deflections due to service loads. There are two methods for prestressing (pre-tensioning and post-tensioning). In this thesis, a three-Dimensional (3-D) nonlinear Finite Element (FE) method is used to determine the behavior of Post-Tensioned (PT) cantilever concrete beams with different tendon profiles. Numerical analyses ANSYS package program is used for analysis of beams. The results from FE analysis is verified by experimental reference test result and good agreement is achieved. To investigate the effect of different tendon profiles on the flexural behavior of Bonded Post Tensioned (BPT) cantilever reinforced concrete beams, six models are chosen. These models are without tendons, two tendons at the bottom, middle, top, parabolic tendons with one draped point and two draped points. Failure loads, deflections, and load versus deflection relationships for all models are examined and it is seen that the beam with one draped tendon profile shows the highest performance.

Keywords: Nonlinear finite element analysis, bonded post tensioned, cantilever concrete beams.

ÖZET

FARKLI PROFILLERE SAHIP ARD GERMELI BETONARME KONSOL KIRIŞLERIN DOĞRUSAL OLMAYAN SONLU ELEMANLAR ANALIZI

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Danışman: Doç. Dr. Nildem TAYŞİ
Haziran 2017
59 sayfa

Dünyanın her yerinde öngermeli beton yöntemi, binaların, köprülerin, kulelerin ve deniz yapılarının kısa derinlik ve geniş açıklık ihtiyaçlarını karşılamak için verimliliği ve ekonomikliği nedeniyle, yaygın olarak kullanılan bir tekniktir. Öngerme betonarme yapıların kırılma yüklerini arttırarak ve servis yükleri altında yer değiştirmelerini azaltarak eğilme mukavemetinin güçlendirilmesi için kullanılır. Ön gerilmeli beton için iki yöntem vardır (ön germe ve ard germe). Bu çalışmada, farklı tendon profilleri ile ard germeli (PT) konsol beton kirişlerin davranışını incelemek için üç boyutlu (3-D) doğrusal olmayan Sonlu Eleman (FE) yöntemi kullanılmaktadır. Kirişlerin sayısal analizleri için ANSYS paket programı kullanılmaktadır. FE analiz sonuçları referans bir kaynaktan alınan deneysel test sonuçları ile doğrulanmış ve iyi bir uyum sağlandığı gözlemlenmiştir. Farklı tendon profillerinin yapışık ard germeli (BPT) konsol betonarme kirişlerin eğilme davranışı üzerindeki etkisini incelemek için altı farklı tendon profillerine sahip model seçilmiştir. Bu modeller tendonsuz, ikişer tendon altta, ortada, üstte, parabolik tendonlarda ise bir ve iki dönüm noktası bulunur. Tüm modeller için kırılma yükleri, yer değiştirmeler ve yük-deplasman ilişkileri incelenmiş ve bir dönüm noktalı tendon profili bulunan kirişin en yüksek performansı sergilediği görülmüştür.

Anahtar Kelimeler: Lineer olmayan sonlu elemanlar analizi, yapışık ard germe, konsol betonarme kiriş.

To my parents….

ACKNOWLEDGEMENT

I would like to express my special appreciation and thanks to my supervisor Assoc. Prof. Dr. Nildem TAYŞİ, for all her help, patience, valuable advice, always providing and guiding me in the right direction. I'm very grateful and proudest to work under her academic guidance.

I would like to express truthful appreciation to my co-supervisor Dr. Abbas H. Mohammed for his patience, guidance, and support throughout this study.

Special thanks to my family. Words cannot express how grateful I am to my father spirit that his words lead me to get certificates and my mother for all of the sacrifices that have made on my behalf. Also to all my sisters. I am greatly indebted to my wife, for their strong encouragement during the years of my study.

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LIST OF SYMBOLS/ABBREVIATIONS

3-D	Three Dimensional
ACI	American Concrete Institute
BPT	Bonded Post-Tensioned
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
PT	Post-Tensioned
UPT	Unbonded Post-Tensioned

CHAPTER 1

INTRODUCTION

1.1 General

Concrete is a widely used material which used in structural engineering construction by different ways. It is very strong in compression but tension zones are too weak. Concrete tensile strength is changed and differs between ranges from 8 to 14 percent of its strength in compression. Cracks appear in tension zones after applied loadings due to weakness in tension zones. Some technics were appeared to prevent such cracks from increasing, one of them carried out huge compressive force longitudinally along or parallel to the axis of the structural elements, and this force can prevent cracks from growing by removing and significantly reducing the tensile stress. Thus this force effects raising of shear, bending and torsional capacity of the sections of the element, the sections are then able to behave elastically. After load applications, concrete will have a full capacity which can be powerfully used in the entire depth of the concrete sections. This moral technic was called prestressing force (Nawy, 2011). Figure 1.1 illustrates the response of concrete beams under service load and effect of prestressing for a structural concrete member subjected to tension.

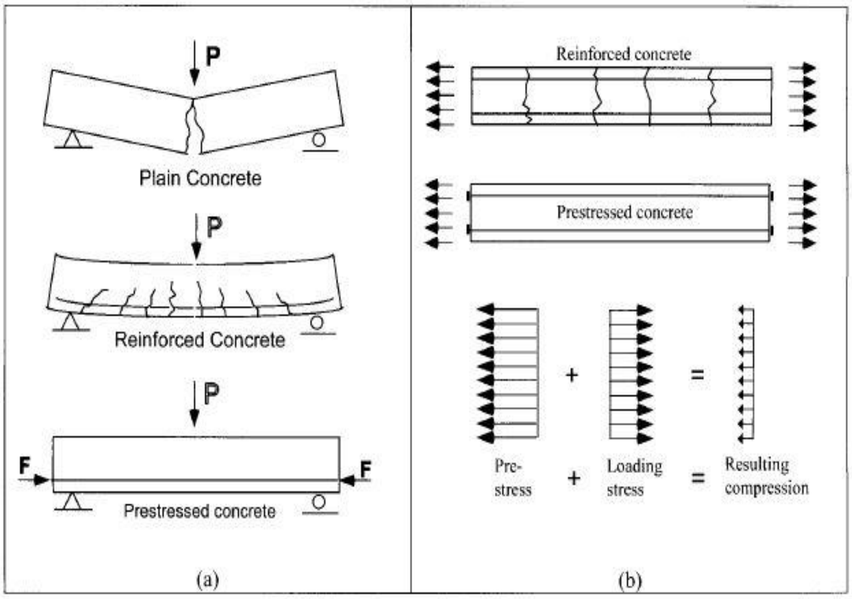

Figure 0.1 (a) Response of plain, reinforce, and prestressed concrete to service loading. (b) Internal stress designed to balance external stress in prestressed tensile members (Naaman, 1982)

The main objective of this study involves a detailed analytical investigation of the flexural behavior of post-tensioned prestressed cantilever concrete beams with different bonded tendon profiles. This will be achieved by non-linear Finite Element Analysis (FEA) programs method, to choose the most effective and optimum position of tendon profiles with different applied load cases on cantilever concrete beams. ANSYS computer program will be used for non-linear FEA based on incremental-iterative load methods, this program is a highly acceptable and reliable commercial software for FEA.

1.2 Finite Element Method

Since the start of computers in the 1940s, the Finite Element Method (FEM) technique has been rapidly developed. In recent years, the use of the FEA has increased due to progressing knowledge and capabilities of computer software. Now FEM has applied for the analysis of the reinforced concrete structures, to understanding the response of reinforced and prestressed concrete beams due to transverse loading, with behavior in both linear and nonlinear ranges. FEM subdivides large structures into smaller, simpler parts that are called FEs, then reconnect element parts by nodes. Ngo and Scordelis,

(1967) firstly applied FEM to the reinforced concrete structures, they used predetermined cracks to simulate the cracks in the concrete as shown in Figure 1.2.

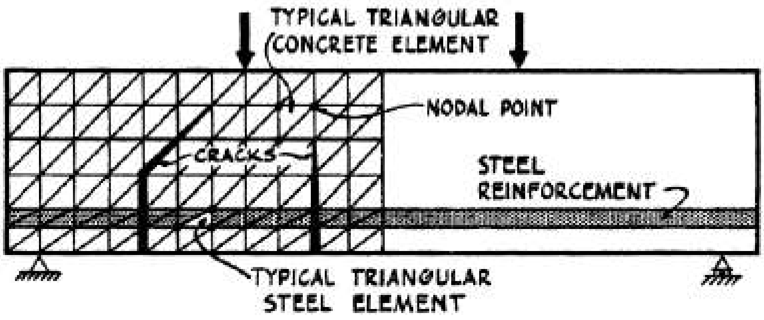

Figure 0.2 FEM of reinforced concrete beam (Ngo and Scordelis, 1967)

The concrete cracking, crushing, the interaction between concrete and reinforcement and the capability of the concrete to transfer shear after cracking by aggregate interlock can be idealized and represented by FEM.

FEA provides a tool that can simulate and predict the responses of reinforced and prestressed concrete members. Generally, nonlinear material models have been integrated for many purposes. FE programs are ABAQUS, STRAND7, ANSYS, or MSC NASTRAN. Those FEA programs play an important role in nonlinear response analyses, each material component tends to possess the complicated stress-strain behavior. Among those computer programs, ANSYS package is chosen for the FEA with Three-Dimensional (3-D) of reinforced concrete structures (Dahmani et al., 2010).

1.3 Post-Tensioned Method

Post-Tensioned (PT) method is a widely used technic all over the world used for structures, to prevent cracks and minimize deflections which are produced by externally applied loads. In this method, stress is applied after concrete placing and reach adequate hardening and strength. The tendons are covered with ducts before concrete casting, after concrete reach hardening, each tendon must be stressed by using stressing jacks to the desired load. To maintain the PT force, all tendons must be anchorage at the ends of the member. This tension stress counteracts with the external live and dead loads to reduce deflections and cracks. By PT method, greater applied loads, greater spans with the same member depth, crack controls and smaller member sizes can be attained. Also, in steel structures it can be used to improve seismic capacity and can be used both internally and externally. As well as it can be used for repair and strengthening of existing structures. Extra structures are being constructed by the PT method such as PT slabs, segmental bridges, continuous beams with long spans, parking, etc. The PT can be used in precast and cast in place. Also by this method, a combination of both bonded and unbonded tendons can be used in the same member, which increase clear span without large member depth. Such examples are constructed in the South Korea and in the US (Ozkul, 2007).

1.4 Problem Statement

When applying external load on the Bonded Post-Tensioned (BPT) beams, the change in strain in tendons at any section is equal to the change in strain in adjacent concrete section. This tendon strain depends on the deformation of strain in concrete section. The profile of tendons affects the strain and failure loads of the beam members. In PT concrete beams, tendons are classically placed continuously through the supports. Most of the past analytical studies and tests are focused on simply supported flexural members. The use of nonlinear FE modeling is limited, while little researches have been performed particularly for cantilever members. This study provides a large overview of some of the key factors and the lacks for simple and reliable design procedures in the PT cantilever concrete beam structures. The ultimate capacity of cantilever concrete beams and failure loads cannot be evaluated by a local analysis of the critical section. A nonlinear analysis of the whole beam structural system is required. The FEM was chosen for its ability to model irregular structures and loading conditions.

1.5 Research Objectives

The main objective of this study to find out the effect of various tendon profiles on the flexural behavior of BPT reinforced concrete cantilever beams, also this study aims to grow comprehensive analytical models to predict the history of entire load deformations of PT cantilever concrete beams with different positions of tendon profiles. Nonlinear FEA will be achieved to find optimum position of tendon profiles under different load cases. ANSYS computer package program will be used for these purposes. Optimum tendon profiles will decrease cost and increase load carrying capacity, so optimum tendon profiles may be recommended after this analysis.

1.6 Layout of Thesis

In order to achieve the objectives mentioned above, this thesis is organized into five chapters.

Chapter one covers a brief description, the aim, and objective of the thesis.

In chapter two briefly, the background and reviews on the previous studies on prestressing techniques which covers the existing experimental and analytical investigations will be given.

Chapter three explains FE modeling and ANSYS computer program to analyze concrete beam models, which includes all material properties and modeling parameters.

Chapter four presents and compares the results obtained from nonlinear analyses of each model. Includes load-deflection relationships at mid and end points.

In chapter five, the conclusions from the overall results of the analysis will be given.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Prestressing method is define as concrete with embedded reinforcements in it to produce internal stress, this internal stress counteracts with external service loads to a preferred degree. This method is done by applying high stress to reinforced tendons in zones, which cracks takes place in it due to external loadings, and then it gives a section that has the ability to resist higher loads before cracking occurs. This system increases the external load capacity to crack (Abeles, 1965). The prestressed method has much application, especially in concrete constructions. A large part of bridges in the US is constructed by the prestressed system. Two different methods were used for prestressing concrete system: pre-tensioned and post-tensioned (Allouche, 1999).

In the pre-tensioned method, stress is applied to the tendons before concrete placing. In this method, tendons are tensioned in a stressing bed. The formwork gathering is placed with stressing beds and anchorages at the ends, then concrete placing is done. After concrete reaches adequate strength, strands must be released at the ends. This operation produces big internal forces, the forces produced by tendons are transmitted to the concrete member by bonds between tendon and concrete. This method usually used in precast constructions when many identical elements are required (Allouche, 1999).

In the post-tensioned method, stress is applied to the tendons after concrete placing. Ducts are used to obtain the desired profile and to allow free movement of tendons in the member. When the concrete has gained sufficient strength, each tendon is stressed to the desired load by using a stressing jack and anchored at each end of the member to maintain the prestressing force in the concrete. PT method is a widely used technic used all over the world for reinforced concrete structures, to prevent cracks and minimize deflections that produced by externally applied loads.

In this chapter, a review of published experimental and analytical studies carried out on internally and externally PT concrete beams will be provided. The main parameters affecting the behavior of PT concrete beams such as area and depth of non-prestressing steel, span-to-depth ratio, loss of prestressing force due to creep and shrinkage of the concrete, as well as relaxation of the prestressing tendons, location of tendons, force in tendons, and types of loading had been investigated, especially for simply supported and continuous reinforced concrete beams. This chapter points out the various researches related with the beams PT and reviews the developed predictions of the stress at failure in the bonded and unbonded tendons through experimental works were undertaken by different researchers. As well as this chapter deals with previous studies related to the FEM and the analytical models by ANSYS package program to investigate the flexural response of bonded and unbonded prestressed concrete beams.

2.2 Post-Tensioned Method

The PT method is a widely used technic all over the world used for structures, to prevent cracks and minimize deflections, which produced by externally applied loads. By PT method, greater applied loads, greater spans with the same member depth, crack controls and smaller member sizes can be attained. According to bond types, there are two different PT concrete members: (bonded and unbonded post-tensioned).

2.2.1 Bonded post-tensioned

In BPT, the stressing force in PT system is held by bonds between surrounding concrete and tendons. The adhesion between steel tendons and concrete significantly affects the resistance of the PT members. The bond between concrete and strands is mobilized by the transformation force of strands to concrete (Hoyer, 1939). In BPT system there is a space between the tendons and ducts, cement mortar is inserted in under pressure to fill this space, which significantly increases the bond and strain compatibility between tendons and concrete, also totally it can protect the tendons against corrosion (Allouche, 1999). BPT can be used in all environmental conditions. BPT has not needed a large area of tendons to obtain the required strength as compared to Unbonded Post-Tensioned (UPT). The tensile stress moves from nearby concrete to the reinforcements, due to the adequate bonds. BPT can be precast or cast in place. The change in tendon strains at any section is equal to the change in strain in adjacent concrete section. The tendon strains depend on the strain changes in the concrete section.

Warwaruk et al. (1962) experimentally tested eighty-two simply supported partially prestressed concrete beams. The purpose of their study was to indicate the effects of changing the concrete compressive strength, the amount of reinforcing steels and types of loading on stress in the prestressing tendons. Their results showed that in the case of using beams without using adequate reinforcements were failed with one major crack, while in beams with using adequate and developed reinforcements predict multiple cracks before failed, additionally, in the case of using tendons, the beams remained elastic ranges at ultimate stress in tendons.

Berkeley (1967) used special link element bonds to connect steel with concrete, by analyzing a simple beam. Constant strain triangular elements were used to present concrete and steel reinforcements. A linear elastic analysis was executed on the beams with predefined crack patterns to determine principal stresses in the concrete, stresses in the steel reinforcement, and bond stresses. The same approach has been used by (Ngo et al., 1967) to study shear in beams with diagonal tension cracks. The effects of the aggregate interlocks, dowel shear, stirrups, and horizontal splitting along reinforcement near the support should be considered.

Tao and Du (1985) in their experimental study twenty-six prestressed concrete beams were tested, different amounts of bonded and unbonded steels were used. To predict the effects of changing amounts of non-prestressed reinforcements, prestressed steel, and concrete strength on the prestressed stress of tendons. Their results showed that by decreasing the total amount of reinforcements (bonded and unbonded) the tendon stress increased at failure. In the case of using a low amount of reinforcement, the beams behave more ductile as compared with beams with a high amount of reinforcement used. The same results were obtained by (Chakrabarti et al., 1994) who reported that by increasing the total amount of reinforcements at ultimate load the stress changes in the unbonded steel tendons were smaller.

Rao and Vegh (1986) experimentally tested three PT reinforced concrete beams and three bonded beams. All beams were simply supported and rectangular in sections. The aim of their tests was to predict the relationships between loads and deflection as well as to predict the growing cracks at nominal flexural capacity. Their results showed that the deflection behavior of unbonded beams provided similar behavior as that of bonded tendons, and flexural strength of unbonded tendons underestimated according to both Indian Code (1980) and ACI 318-77 equations which were 7.5 % and 5.0 % Respectively.

Seible et al. (1990) performed tests of four pre-tensioned concrete beams under applying point loads. Tendons were harped under two-pint loads with an angle of 4.8 degrees for each point load. Their results showed that by strengthened member, the average strength increased by 115 % when single strand was used. The deflections at mid-span at the ultimate load were about 60 % of the corresponding beam deflections. Beams reach failure when concrete crushed.

Manalip et al. (1994) experimentally studied five beams of high strength concrete. Beams were subjected to pure bending and analyzed to measure their ductility and to realize the real strain-softening behavior of their compressed zones. For the experimentally tested beams, it was found that the use of high strength concrete instead of normal strength concrete effects the results by the doubling of the plastic rotation capacity.

Hussien et al. (2012) presented an experimental program to study the behavior of bonded and unbonded prestressed beams with high strength and normal strength concrete. Their results showed that by using partially prestressed concrete beams with bonded tendons provide better behavior than those of unbonded tendons, and by Increasing the nominal compressive strength from 72 to 97 MPa for bonded prestressed beams, increase in the ultimate and cracking loads by 4 % and 18 %, respectively. The analytical work was introduced and compared to the results of the experimental work and gives a good prediction.

Nusrath et al. (2015) studied the effect of different tendon profiles and the cable curvature on the construction of a structure to achieve greater strength and at the same time making the structure economic. The service limit states and ultimate limit states were used for evaluating optimization. Their results found out that a parabolic profile is most economical when compared to rectangular profile, similarly, a trapezoidal profile is most economical than a parabolic profile.

2.2.2 Unbonded post-tensioned

When mortar or grout not used to fill the spaces between tendons and ducts, then it is called Unbonded Post-Tensioned (UPT) system, instead, naturally filled with grease as a protection against corrosion. In UPT may be avoided the expensive of time-consuming of grouting operation, it is an economical alternative to conventional to bonded prestressed. This system has some problems, which stopped it from being more widely used, the unbonded system cannot be used in corrosive environments due to disposed of corrosion like bridges (Nowak, 1994), but may be used in parking structures with offering suitable protections against corrosion (Litvan, 1996). This system requires a larger area of tendons to obtain the required strength because of the ultimate strength of unbonded tendons about ten to thirty percent lower than bonded members (Park and Paulay, 1975). The behavior of UPT tendons does not wholly understand yet. Furthermore, it has not had a modest and accurate method for predicting the stress in unbonded tendons at failure. The tensile stress cannot be moved from nearby concrete to the reinforcements due to the lack of bonds, thus the cracking pattern at failure characterized by single or little cracks in the maximum moment region.

Burns and Pierce (1967) experimentally tested fifteen beams with prestressed unbonded tendons. Their tests focused on the relationship between loads and deflections, and growing cracks at ultimate load capacity. Their results showed that by using non-pretsressed unbonded tendons provides an acceptable performance for strengthening. Strands give a great role in controlling cracks and strength, for both shear strength and flexural. ACI Building Code (1963) equations provided very traditional predictions. In continuous beams when using sufficient shear reinforcements it can develop plastic hinging at the point of the highest moment before reaching ultimate load capacity.

Mattock et al. (1971) experimentally observed that the plastic deformation happened in plastic regions in the prestressed reinforced concrete members, which affects the total elongation of the prestressed steel between the anchorage ends. This is a contribution of the curvature distribution between zero and yield to the total elongation of the tendon. The stress in the unbonded tendons is constant along the length at the nominal flexural strength of the beams. According to the ACI Building Code (1983) assumptions, the strain on the concrete compressive zones at the top beams fiber, the total increase in the tendon elongation between the anchorages, and the strain increase in the tendons could be derived.

Tam and Pannell (1976) experimentally used eight partially prestressed beams with unbonded tendons. The span to the depth ratio, prestressing stress, and non-prestressing reinforcing steel amounts were fixed. Their results showed that diagonal cracks occurred, which cut across the flexural cracks in the case of using high reinforcement index. Furthermore predicts, at the ultimate load capacity a limit of small concrete strain appeared, the plane sections before loading remains after loading.

Mojtahedi and Gamble (1978) their study was focused on the effect of the span to the depth ratio of the ultimate stress of unbonded tendons. Their results showed that at ultimate nominal resistance, the stress in prestressing steels has been significantly affected by span to the depth ratio. Increasing the span to the depth ratio, effects on the stress of unbonded tendons, which reduced at ultimate. Conclusions supported by using the analytical model of the truss, the analysis showed that the strain in a tie at mid-span decreased suddenly as the span-to-depth ratio increased. To continue the same result were verified on a parametric study on externally PT concrete beams by (Harajli, 1990).

Chakrabarti and Whang (1989) experimentally published the cracking and ultimate strength behavior of simply supported reinforced concrete beams with partially prestressing of unbonded tendons. Eight beams have been tested. Their results showed that at the ultimate load the tensile steel bars reach yielding, failure occurs by concrete crushing at the ultimate load. By decreasing of partially prestressed ratio the stress in the steel bars increased. To predict the stress in the unbonded tendons at ultimate, the non-prestressed and compressive reinforcements should be taken into account in the ACI 318-83 equation. Test results were reported with specific conclusions and recommendations for future design and code revisions.

Harajli (1990) presented a theoretical model for unbonded prestressed concrete members to evaluate the influence of the effect of the span-depth ratio parameters on the stress in prestressed steels. Harajli showed that the increase in stress in unbonded prestressing steels mainly depends on the geometry of the applied loads and depends on the plastic region length relative to the span length. By increasing span to the depth ratio decreases the predicted stress.

Bums et al. (1991) experimentally tested two continuous PT concrete beams with internally unbonded tendons to predict change in the prestressing force in tendons. The results showed that the tendon forces under cycle service loads did not change up to the compressive stress level of ($12\sqrt{fc^-}$). When the beams overloaded in just single span, tendons are tended to slide into a loaded span, this causes stress in tendons decreases on the end of the loaded beam span and increases stress in the unloaded span at the end. In the case of applying two spans loaded, the distributed stress in tendons did not change significantly. Furthermore predicted that by using of draped tendon profiles, the change in tendon stress for a given deflection was larger than the corresponding beam with less of severing draped profiles.

To study the effect of several parameters on the magnitude of the prestressing stress of steel, Harajli and Kanj (1991) tested twenty-six simply supported concrete beams with rectangular cross-sections, prestressed with unbonded tendons and with and without ordinary reinforcing steels. Their results showed that the application of the load types has no significant influence on the stress in prestressed tendons. Also, their results showed that the stress in prestressed tendons in single concentrated load was same in two third-point loads. By increasing the span-depth ratio from 8 to 20 effects in decreasing the stress in the tendons by 35 %. It means the load application was not significantly affected.

Campbell and Chouinard (1991) experimental used six partially unbonded prestressed concrete beams with rectangular cross-sections, their results showed that by increasing the amount of non-prestressed bonded steels decreases the stress in the prestressing tendons at ultimate loads. Their test results were compared with predictions from two related design codes and identified some limitations of these code application to unbonded prestressed concrete construction.

Naaman and Alkhair (1991) suggested a methodology leads the strain reduction coefficients to provide the necessary correlations between the member and section behavior, inelastic uncracked, cracked ranges, ultimate resistance, and nominal resistance. In their study, tests were done on simply supported beams included symmetrically tendon profiles. Effects of diagonal shear cracks were neglected. The analysis of a beam with unbonded tendons is converted to the analysis of a beam with bonded tendons, by using the strain reduction coefficients. They predicted that when only one crack has occurred in the elastic cracked region the strain reduction coefficient must be used.

Alkhairi and Naaman (1993) developed nonlinear models for prediction of moments versus deflection response of reinforced concrete beams with unbonded and bonded prestressed tendons and non-prestressed reinforcements. As well as the verification has been carried out by using fifteen experimental test results investigated from 1962-1990 and good correlation was observed between predicted results and experimental observations.

Dall'Asta and Dezi (1993) studied the Ritz approximation method to solve the stress in the unbonded prestressed tendons. And they suggested that using the concept of total potential energy minimization.

Chakrabati et al. (1994) experimentally tested thirty-three unbonded prestressed reinforced concrete beams. Their results showed that beams with enough reinforcement index and enough partial prestressing ratio have better load caring capacity, better ductility, and performance in the post-cracking range. Using the high amount of partial prestressing ratio caused sudden large cracking in the tension zones and high amount of combined reinforcing index cause crushing in the compression zones. To improve ductility, deflection, and cracking control the partial prestressing ratio should be reduced gradually. In the case of span-depth ratio above 35, post-cracking behavior and deflection control were enhanced. The tendon initial stress had no effect on overall beam behavior, however, the ultimate strength of prestressing steel increased.

Picard et al. (1995) studied the efficiency of tendon profiles for both external and internal prestressing tendons of statically in-determined structures for both parabolic and linear tendon profiles. The results showed that the linear profiles were more effective in support regions in counteracting gravity moments, their efficiency within the spans can be considerably reduced. The optimization of the effective eccentricity was more difficult along all members. They recommended that by using internally prestressed with parabolic tendons gives more uniform efficiency through the structures and recommended using linear draped tendons and localized tendons.

The comprehensive flexural behavior of prestressed concrete beams with external as well as internal unbonded tendons has predicted in the study by (Srinivasa and Mathew, 1996) they outlined a comprehensive analytical method to predict the behavior of externally prestressed concrete beams throughout the entire range of loading up to failure load. All important factors take into consideration of variation of stress in the unbonded tendons due to the deflected shape of the beam. Furthermore, this method is relevant for a general polygonal shaped tendon profile with any number of deviators.

Vu et al. (2010) calculated the structural response of unbonded PT prestressed beams, including both the ultimate bearing capacity and the deflections under service loading, before or after cracking. They predicted the overall lengthening of the unbonded tendons at all loading stages: serviceability, cracking, and ultimate. The calculations of the bearing capacity and the deflection at failure were very accurate.

2.2.3 External post-tensioning

Another method was introduced which was externally PT system, used in many parts of engineering structures, such as in segmental bridge constructions, rehabilitations, strengthening of existing structures, and also used to replace the damaged tendons. By this method, the dimensions of the member sections and member self-weight can be reduced (Allouche, 1999).

Harajli (1993) experimentally studied the strengthening flexural members by external prestressing. For this purpose, he tested sixteen simply supported beams with rectangular cross-sections. The results of his tests showed that the nominal flexural strength of the beams was increased about 146 % by applying externally prestressing tendons, without a reduction in ductility, and the service load deflections were reduced by about 75 % under cyclic fatigue loading. Harajli found that by using draped tendon profile increases the flexural resistance as compared to straight tendon profile. Furthermore, Harajli (1993) assumed that by an increase in tendon elongation between the anchorage ends the strain in the external prestressing steel increases under applied loads, and the proportional between strain in strands and deflections were linear.

AI-Gahtani et al. (1995) reported an effective creation for optimum design of two-span continuous concrete beams with partially prestressed. Different forces on prestressed tendon profiles have been used along the beam length, tendons are anchored at the both beam ends with flexibility in the overlapping location. Their results showed that the design of partially prestressed concrete beams was economic as compared to the designing of fully prestressed concrete beams in two span continuous concrete beams, moreover, the same conclusion was verified by (Colin and MacRae, 1984) for simply supported concrete beams.

Tan and Ng (1997) tested six reinforced concrete beams with external prestressing tendons, the cross sections were T-section for all beams, and all beams were strengthened in flexure using external strands. Their test results showed that by using deviators for beam sections of maximum deflection had a significant effect on satisfactory service load behaviors (cracking, deflection, and steel stress) and had a higher load- carrying capacity as compared to the case where no deviators were used. Their results showed that by increasing eccentricity of straight tendons with a correspondingly smaller prestressing force had a significant effect on makes a larger internal steel stresses, service load deflections, and crack widths with a higher ductility. In the case of using draped tendon profile, significantly effects on stiffness, which was reduced, increase tendon stresses, makes more ductile behavior near failure. Also, the service load behavior was not changed by using a larger tendon area, which gives a lower ductility with higher ultimate strength.

Harajli et al. (1999) investigated a parametric study on concrete beams strengthened by externally straight steel tendons to find out the effect of deviators. Beams had been modeled with deviators and without deviators at mid-span. Harajli et al. (1999) mentioned a second order effect to change the tendon eccentricity with increasing member deformation. This effect can indicate the main differences between the behavior of unbonded external tendons and unbonded internal tendons. By second order effect method the un-deviated external tendons to mobilizing has lower inelastic deformation and lower nominal flexural resistance as compared with deviated tendons. This has a significant effect on improving the service load behavior of the beams and reduces the stiffness due to applied load.

Naghipour et al. (2010) experimentally and numerically studied the behavior of reinforced concrete beams strengthened with externally prestressed tendons. They used a FEM program such as ANSYS to modeling PT reinforced concrete beams. They concluded that the strengthening method was very effective for beams with lower percentages of internal flexural tension reinforcement. Furthermore, they predict the increase in flexural strength caused by the used of unbounded external PT reinforcing bars was in reverse proportion to the percentage of internal flexural tension reinforcement.

2.3 Finite Element Analysis

Concrete structural components exist in buildings and bridges in different forms. Understanding the response of these components during loading is important to the development of an overall efficient and safe structure. Different methods have been utilized to study the response of structural components. Experimental based testing has been widely used as a means to analyze individual elements and the effects of concrete strength under loading.

FEA is a most suitable numerical method, used to solve and analyze complex problems, it is very important to engineering researchers. Recent developments in computer technology make it possible to use FEA computer programs in all engineering branches to dealing with different material properties, boundary conditions, relationships between structural components, and statically or dynamically applied loads.

FEA can determine the response of linear and nonlinear structures with good accuracy. Problems require resolve of the 3-D distribution of one or more dependent variables or elements, mathematically, then this element is express by differential equations or by integrations, these elements are connected at point nodes.

A 3-D FEA is still the most general and comprehensive technique, which is used for static and dynamic analyses, capturing all aspects affecting the structural response. It becomes the numerical method of choice in many engineering and applied science areas (Kim, 2014).

A collection of papers were appeared by several researcher which explain the FEA for the behavior of reinforced concrete structures such as shear failure of beams, cyclic loading of columns, the behavior of structure to seismic, and bond models between concrete and steel.

2.3.1 Finite element analysis of structures

To predict the response of reinforced concrete elements, Vecchio, (1989) developed a nonlinear FE procedure. Based on the secant stiffness formulation. He showed that by nonlinear FE techniques, the response of reinforced concrete members can be predicted accurately, and this technique is enough simple for nonlinear FE formulation.

Vacev et al., (2015) they used nonlinear FEA by ANSYS package program to predict the behavior of reinforced concrete footings and columns under applied concentrated load until failure. The comparison of the field test results and FEA results showed good agreement. Their results showed that the ANSYS FEM is a powerful method for solving even multiple complex structural problems, such is the behavior of reinforced column footings laid on deformable subgrade.

Luu et al., (2017) they developed an FEA to predict the inelastic behavior of reinforced concrete shell structures in the program a cyclic softened membrane model. To confirm the developed FEA program several large-scale structural tests were employed, which including the reinforced concrete panels under the effect of shear and bending, reinforced concrete cylindrical tank and a 3-D reinforced concrete shear wall. Agreements were obtained when analytical results were compared with experimental data. The results showed that, for studying the cyclic response of both curved and flat reinforced concrete shell structures, the newly developed program based on the shell elements could be a powerful and versatile analytical tool.

Li et al., (2017) established the corresponding nonlinear FEA to analyze the mechanical behavior of high-strength concrete filled with high-strength square steel tube under pure bending load. Six specimens with different steel ratio were tested. The obtained load-displacement curves from the numerical analyses are consistent with the experimental results. Experimental tests and FEA results were the most compatible to the calculated result of code EC4 (1994).

Hopkins et al., (2017) they developed a nonlinear FEA model using ABAQUS to study the behavior of panels under typical flexural loading and dynamic behavior under blast loading. The loading time was controlled to slow down the rate of loading to smoothly capture the response of the FE models. A verification study was conducted first using the developed FE model, where good correlations can be obtained between the FE and test results.

2.3.2 Finite element analysis of reinforced concrete beam structures

Dahmani and Kaci (2010) developed a 3-D FEM of reinforced concrete beams. ANSYS program version 8.0, was used for the numerical analyses. Their results compared with hand calculated and presented with the concrete beam, the capability of the model to capture the critical crack regions, loads, and deflections for various types of loading in reinforced concrete beams has been illustrated.

Albrifkani and Wang, (2016) presented a dynamic explicit FEM simulations to predict the nonlinear response of axially and rotationally restrained reinforced concrete beams in the effect of fire and temperature condition. The proposed method has confirmed by checking the simulation results against related available test results. They found that to understand the whole range behavior of restrained reinforced concrete beams under loading until failure can be clearly simulated by FEM.

Jnaid and Aboutaha, (2016) they developed FEM to present the evaluation of the residual flexural strength of reinforced concrete beams, to investigate the effects of length of the corroded zone, corrosion degree, and span to the depth ratio on flexural strength. The FEM was verified against the experimental data obtained by other researchers. Their results showed that the proposed FEA can predict the ultimate flexural strength of unbonded and/or corroded reinforced concrete beams with good accuracy.

Al-Osta et al., (2017) investigated the strengthening of reinforced concrete beams using ultra-high performance fiber reinforced concrete by two different techniques to study the effectiveness and efficiency of reinforced concrete beams. To predict the behavior of the beam specimens, they developed FEA models. The results of the FEA models showed good agreement with experimental results, and FEA has the ability to predict the behavior of the beams with high accuracy. The FEM predicted highest load and load-deflection behavior were close to the experimental test values.

2.3.3 Finite element analysis of prestressed concrete structures

Kang and Scordelis (1980) presented a numerical procedure based on the nonlinear analysis by FEM for the material and geometric of plane prestressed concrete frames, in this method creep, shrinkage, aging of concrete, time-dependent effects due to load history, temperature history, and prestress relaxation were developed. Different material properties inside frame elements were accounted by a composite concrete and reinforcing steel layers. The contribution of prestressing steel was combined directly.

Roca and Mari (1993) described unbonded prestressed tendons. They used the virtual work and FE formulations for the nonlinear analysis of shell elements to solve the problem, by using a formulation for the nonlinear material and geometric proposed numerical treatments, and analyzing long term of prestressed concrete members. The unusual focus was given to such aspects as the geometric description of the layout of the tendons. They focused on the aspect of increment of geometry under external load.

Figueiras and Povoas (1994) explained a technic for structural modeling of prestressed tendons by FEM, for nonlinearly designed structural concrete prestress. To create strand model curved elements that were embedded in FEM has been used for both bonded and unbonded tendons, to finding ultimate strength capacity of prestressed members and the serviceability behavior. The formulation was advanced to be incorporated with curved thick shell elements and the applicability of the computational code is verified by the results of two numerical samples.

Moon and Bums (1997) developed a computer program which was used for analyzing concrete structures by prestressing method for unbonded members and stress variation in the tendons. The program was called (time dependent analysis) program. The total compatibility requirements used for developing analytical models. Total elongation for unbonded tendons equal to the integrated deformation value of concrete. This method can take into account shrinkage, creep, and mechanical deformation of inelastic range in a continuous manner.

Lees and Burgoyne (1999) suggested an analytical model for beams with partially bonded fiber-reinforced plastic tendons. Based on the beam rigid body behavior and compared the model with experimental results. The discrete crack approach used in this model in which the rotation of the beam is assumed to occur only at crack locations. The stress in the tendon, the geometry of the deflected beam, and the bond stress were calculated. The crack formation, bond loss, and tendon rupture were predicted. This procedure was repeated until complete bond failure or tendon rupture happens.

Kachlakev et al. (2001) in their study the computer programs were used to compare tested results for both linear and nonlinear FEs of concrete models. Two programs such as ANSYS, (SAS 2003) were used to find behaviors of concrete beams externally bonded with carbon fiber reinforced polymer fabric. The Newton-Raphson nonlinear approach was used. The convergence solutions of reinforced concrete nonlinear behavior were difficult to complete due to the nonlinearity of reinforced concrete materials. The plotted results of load deflection curves for reinforced concrete beams with non-carbon fiber reinforced polymers shows the reasonable correlation with experimental.

Fanning (2001) discussed a numerical model by ANSYS program, in his study the ordinary reinforced concrete beams with 3-meter-long spans and prestressed beams with long span 9 m have been tested. The load was applied up to failure to predict the response of ultimate reinforced concrete beams. The conclusion showed that a suitable numerical model for taking the flexural modes of failure in reinforced concrete members was dedicated smeared crack model.

Shing and Tanabe (2001) published a collection of papers together for analyzing the inelastic behavior of reinforced concrete structures under seismic loads. The papers explain the applications of the FEA to demonstrate the ductility of reinforced concrete columns under post-peak cycling behavior, analysis of reinforced concrete components in bridge seismic design, connections between beam-column, and shear behavior in reinforced concrete bridge analysis.

Ariyawardena and Ghali (2002) analytically predicted the behavior of prestressed concrete structures with internal or external tendons up to ultimate. The analysis includes the effects of tension stiffening, geometric, and material nonlinearities. The computer program developed to perform analysis method, the analysis method was verified by using experimental study on simple and continuous beams with internal or external tendons.

Lou and Xiang (2006) developed a nonlinear FEM to a numerical model of concrete beams prestressed with external tendons. The second-order effects were taken into the account. Their predicted results have good agreement with the experimental data. Their analytical results showed that the load–deflection curves and moment versus stress increased in tendons of externally prestressed concrete beams with a certain amount of ordinary bonded reinforcing.

Du et al. (2008) described a numerical method for the full-range analysis of prestressed concrete flexural members with unbonded tendons, to find out the effect of loading type, concrete compressive strength, span–depth ratio, partial prestressing ratio, combined reinforcement index, and the ratio of compressive reinforcement. The numerical results were compared with an experimental result. Their results showed that by increasing of combined reinforcement index the curvature ductility factor of prestressed concrete member decreases, and the span–depth ratio has almost no effect on the curvature ductility factor of an unbonded member.

Ibrahim (2010) presented the parametric study of the flexural behavior of prestressed continuous concrete members with external tendons, to find out the effects of several factors that affects the behavior of prestressed members at ultimate limit states. A 3-D nonlinear FEM by ANSYS computer program was used. The analysis was verified with the experimental results and give good agreement. Results showed that by increasing the effective depth will increases the ultimate load capacity, the increase in the beam capacity in the beams subjected to loads at the third span were bigger than in the beam with a single load at mid-span.

Joshuva et al. (2014) analyzed a nonlinear behavior of reinforced and pre-tensioned concrete beams under external loading. The FEM by ANSYS version 12.0, was used. Load-deflection responses, variations of stresses in concrete and steel, and the crack patterns at critical stages of loading were studied. Their results by the numerical method of analysis using ANSYS computer program was seen to satisfactorily predict the behavior responses of the beams up to ultimate.

Lou et al. (2016) analyzed the parametric study to predict the behavior of two-span continuous prestressed concrete beams with internal unbonded fiber reinforced polymer and steel tendons. A nonlinear model was verified by the experimental results. Their analytical results showed that the type of unbonded tendons has practically no influence on the cracking mode and moment redistribution, while it has limited effects on the development of deformation. They proved that, the type and amount of bonded steel bars affect significantly on the member behavior.

2.3.4 Finite element analysis of post tensioned concrete structures

Nikolic and Mihanovic (1997) proposed a FEM to analyze the PT members. The concrete was modeled by an eight-node two-dimensional element associated with the smeared crack approach and concrete material model which combines the elastoviscoplastic approach. The tendons were expressed by a one-dimensional isoperimetric three-node element with a uniaxial stress-strain relation. The friction prestresses loss was taken into account by considering that a distributed load due to prestress within a tendon consists of the normal and tangential parts with respect to the tendon direction. The model was tested on a number of examples, the numerical results gave a good agreement with the available experimental data and previous analyses were done by other investigators.

For simulating the nonlinear flexural behavior of UPT beams and developing a 3-D FEA, a study has been done by (Kim et. al., 2010) in their study the FEA by ANSYS program has been used to examine the effects of different prestressing forces on the flexural behavior of UPT concrete beams. Four PT concrete beams were tested in California state university. The results were compared with the analytical results by ANSYS program which showed that the 3-D FEA was able to simulate the PT concrete beam behavior, the strain produced by ANSYS program gives a good agreement with the strain by experimentally tested specimens.

Kim and Lee (2012) used nonlinear analysis method to finding the flexural behavior of continuous UPT members, this nonlinear analysis reflects the moment redistribution. The verification has been done to finding the accuracy of proposed analysis model, for this purpose the analysis test results was compared with experimental results. The results of their study showed that the loading type effect on the flexural behavior of continuous UPT, which was reflected by curvature distribution in the region of maximum moment and the accuracy of flexural behavior of the proposed analysis model were constant, irrespective of the type of applied loads, section shapes, and tendon profiles.

Package ABAQUS program was used to model the PT structures with bonded and unbonded tendons by (Kang and Huang, 2012) three modeling approaches had been used to simulate unbonded and bonded tendons, compared all approaches with the analytical and experimental results. The first approach was based on contact technic which reflects tendons in concrete in true physical conditions. The second approach was a multiple-spring system that offers more flexibility in modeling and strength in convergence subjects. The third approach was the model using a contact formulation (surface-to-surface contact). Their results showed that the third method of the contact formulation was the most computationally efficient, and the developed model was capable of simulating for both bonded and unbonded tendons quite effectively.

Yapar et al. (2015) simulated the FEM to find out the behavior of PT prestressed concrete beams. Their results have a satisfactory agreement between FE predictions and test results of the beam under loading to collapse load. The FEM developed and accurate for pretension beams based on a plasticity damage and bond slip failure model.

Izzet and Dakel (2015) studied the behavior and load carrying capacity of PT concrete beams exposed to fire flame. A 3-D FEM program such as ANSYS was used to investigate the structural behavior under the effect of burning by fire flame exposed to PT concrete beams. Their results showed good agreement between the FEM results and the experimental results throughout the load-deflection behavior before and after burning. The crack patterns at the final loads from the FEM agreed well with the observed failure modes of the tested beams.

Izzet (2016) studied the effect of high temperature on the strain behavior of PT concrete beams exposed to fire flame. A 3-D nonlinear FEM was used to idealize the effect of burning by fire. His results by FEA have a good agreement with experimental results throughout the load-deflection behavior before and after burning as well as showed that 3-D nonlinear FEM was able to simulate the behavior of PT concrete beams. He noticed that the strain increases when the temperature increased.

2.4 Summary

Most of the previous researchers carried out their studies on simply supported with externally PT concrete elements. The most significant parameters that effect on these elements were reported to predict the effect of different parameters on the behavior of externally and internally PT members. Such parameters as the amount of bonded reinforcement, the span-to-depth ratio, the level of prestressing in the external tendons, the stress in the unbonded steel tendons at ultimate stages, load-deflection response, and cracking loads.

The literature review submitted some experimental researches and results has been verified by a numerical FEM program with good agreements. So the researchers suggested that the use of FEM by ANSYS package program can be used for modeling and analyze of reinforced and prestressed concrete beams.

Up to date, there is no comparative study and experimental works to model the behavior of internally BPT reinforced cantilever concrete beams with different tendon profiles, as well as internally BPT cantilever concrete beams has not been interested. This study will focus on the effect of BPT with different tendon positions. And the FEM results will be verified with an experimental result, in order to certify the proposed nonlinear model. The numerical results of load–deflection curves will be verified with experimental results tested by (Hussien et al. 2012).

CHAPTER 3

FINITE ELEMENT MODELING

3.1 General

This chapter discusses the FE modeling of PT concrete beams. The FEM is one of the numerical methods for solving engineering problems and mathematical physics that characterized by a variation formulations and differential equations. The FEM first invented from the structural mechanics then it had been extended to other areas of solid mechanics such as heat transfer, fluid dynamics, and electromagnetic. FEM is a most powerful tool for solving partial differential and integrational equations. It becomes an important and regularly method of engineering analysis because requires minimal amounts of training to solve many complex practical problems with support of versatile computer programs (Kim, 2014).

3-D FE modeling is probably the most involved and time-consuming, it is still the most general and comprehensive technique for static and dynamic analyses, capturing all aspects that affecting the structural response.

Several methods for modeling the concrete structural elements both analytically and numerically appeared. FEA is a numerical analysis widely applied to the concrete structure elements based on the use of the nonlinear behavior of materials, FEA provides a tool that can simulate and predict the responses of reinforced and prestressed concrete members (Dahmani et al., 2010). In recent years, however, the use of FEA has increased due to progressing knowledge and capabilities of computer software and hardware. It has now become the choice method to analyze concrete structural components. The use of computer software to model these elements is much faster and extremely cost-effective. Complex geometries like PT reinforced concrete beams with tendons can freely model and analyzed by using the FEA. One of the FEA programs is ANSYS package computer program used for solid modeling, it is a highly acceptable and reliable commercial FEA program. It has the ability to structural nonlinear modeling and analyzing.

3.2 Basic Steps in the Finite Element Method

The basic steps involved in any FEA consist of the following steps (Bathe, J., 1996):

1. The structure is created and divided into FEs connected together at their nodes.

2. A shape function is assumed to represent the physical behavior of an element; that is, an approximate continuous function is assumed to represent the solution of an element.

3. Equations for stress distribution and stiffness are developed for an element.

4. The assemblage of FE equations to present the entire problem, then the global (or structural) stiffness matrix is constructed.

5. Boundary conditions, initial conditions, and loading are applied.

6. A set of linear or nonlinear algebraic equations is solved simultaneously to obtain nodal results, such as displacement values at different nodes, or other important information such as stresses and strains that can be obtained for the nodes or the elements.

3.3 ANSYS Finite Element Modeling

ANSYS is a general-purpose FEA package for numerically solving a wide variety of complex engineering problems both linearly and non-linearly. It is a numerical method of deconstructing complex models into actual small pieces called elements. The ANSYS software implement equations that govern the behavior of these elements and solves all of them. After solving, the results can be presented in the tabulated or graphical form. For setting up any FEA in this software, it may undergo three stages. The first stage is preprocessing, in this stage, the solid model will be defined, which consist of define key points, lines, areas, and volumes, then define element types and material geometric properties, finally define meshing of lines, areas, and volumes. The second stage is solution stage, in this stage, the boundary conditions, load assigning, and solving control will be defined properly. The third stage is post-processing, at this stage, the overall results of the analysis will be viewed, such as lists of nodal displacements, deflection plots, stress contour diagrams, and element forces and moments etc.

When the model meshed, volumes, areas, or lines can not be deleted because they are connected to the existing meshed elements. Depending on the size and shape of the complete solid model, ANSYS contains many solid FEs to choose, each having its own specialty. The structural analysis must be choosen as the type of analysis (Madenci and Guven, 2015).

3.3.1 Concrete modeling

The model used for concrete idealization must have the ability to existing concrete crushing in compression, concrete cracking in tension, the capability to transfer shear after cracking by aggregate interlock and interaction between concrete and reinforcements (Izzet, 2016).

SOLID65 (or 3-D reinforced concrete solid) in ANSYS used for modeling the concrete, this element has eight nodes and three degrees of freedom at each node, nodes in the x, y and z-directions are translated, it means that concrete can crack in three orthogonal directions, plastic deformation and creep. The behavior of this element is worked as a nonlinear isotropic material properties. The geometry, node locations and the coordinate system for this element are shown in Figure 3.1 (ANSYS, 2011).

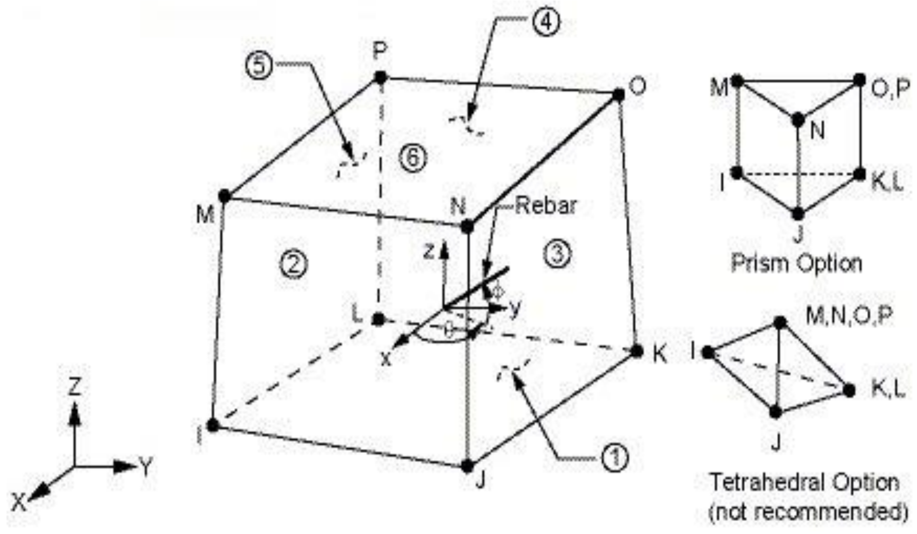

Figure 3.1 SOLID65 geometry (ANSYS, 2011)

3.3.2 Steel reinforcement and tendon modeling

The model that used for reinforcements idealization must have the ability to existing plasticity, creep, swelling, stress stiffness and large deflection, to show the behavior of steel reinforcements, ties reinforcements and prestressing tendons. Three technics are used to model reinforcements, which are discrete, embedded and smeared technics (Tavarez, 2001).

LINK8 is a discrete model and spare element, which is used for many engineering applications, by this element the trusses, links, sagging cables, and springs can model. This element is a 3-D spare and uniaxial tension-compression element. Link8 has 3 degrees of freedoms at each node, nodes in the x, y and z-directions are translated, no bending of the element is considered (ANSYS, 2011).

The prestressing stress is the initial value of the strain in this link element. The PT force has transferred through the beam and connected at the ends by anchorages. The geometry, node locations, and the coordinate system for this element are shown in Figure 3.2.

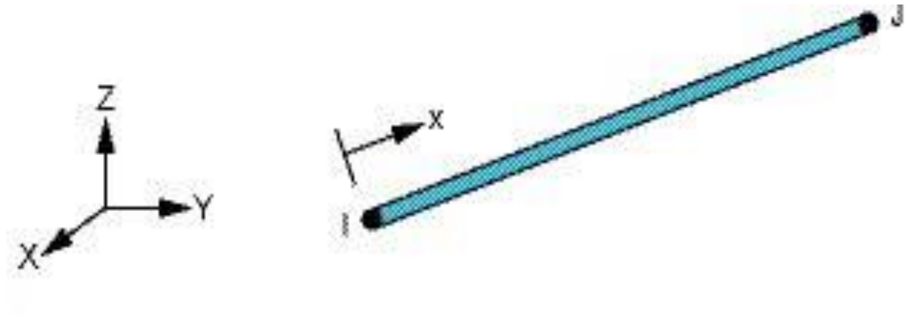

Figure 3.2 LINK8 geometry (ANSYS, 2011)

3.3.3 Anchorage steel modeling

The tendons must be anchored at both ends of the beam members to maintain internal forces, these forces create high stress at both ends, to avoid the ends from crushing the shell plates must be applied at the ends.

SHELL181 is suitable for analyzing thin to moderately thick shell structures. It is a four node element with six degrees of freedom at each node, translations in the x, y, and z directions, and rotations about the x, y, and z-axes. The geometry, node locations, and the coordinate system for this element are shown in Figure 3.3 (ANSYS, 2011).

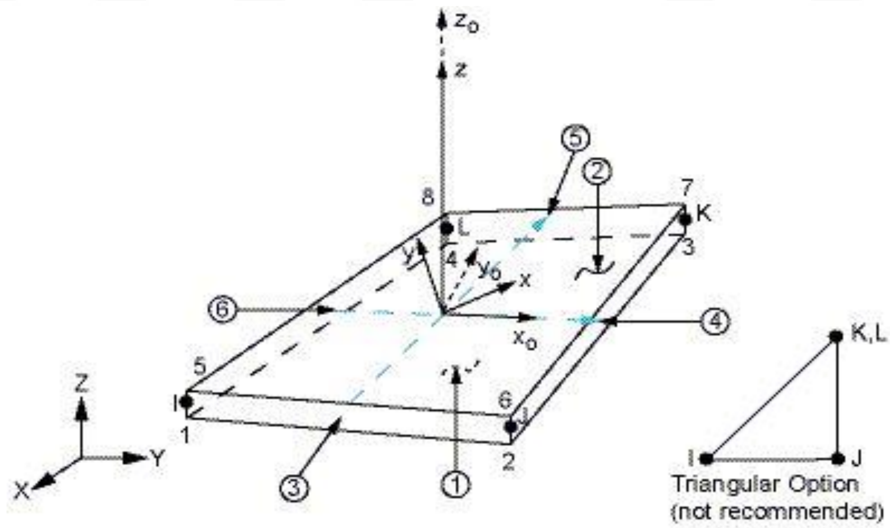

Figure 3.3 SHELL181 geometry (ANSYS, 2011)

3.3.4 Bearing steel plate modeling

To avoid crushing at point loads the bearing plates are used. SOLID45 is used for the 3-D modeling of solid structures. This element is defined by eight nodes having three degrees of freedom at each node, nodes in the nodal x, y, and z-directions are translated. This element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. The geometry, node locations, and the coordinate system for this element are shown in Figure 3.4 (ANSYS, 2011).

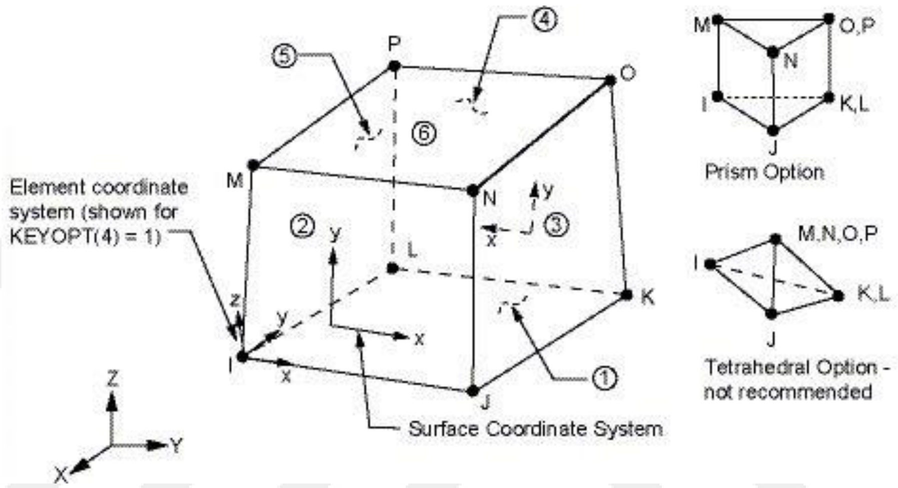

Figure 3.4 SOLID45 geometry (ANSYS, 2011)

3.3.5 Contact modeling

TARGE170 is used to represent various 3-D "target" surfaces for the associated contact elements CONTA175, the contact elements themselves overlay the solid, shell, or line elements describing the boundary of a deformable body and are potentially in contact with the target surface, defined by TARGE170. This target surface discretized by a set of target segment elements TARGE170 and paired with its associated contact surface via a shared real constant set. It can impose any translational or rotational displacement, temperature, and magnetic potential on the target segment element. For rigid target surfaces, these elements can easily model complex target shapes. For flexible targets, these elements will overlay the solid, shell, or line elements describing the boundary of the deformable target body.

CONTA175 is used to represent contact and sliding between two surfaces (between node and surface, or between line and surface) in 2-D or 3-D. The element is applicable to 2-D or 3-D structural and coupled field contact analyses. This element is located on the surfaces of solid, beam, and shell elements. 3-D solid and shell elements with mid-side nodes supported for bonded and no separation contact. Contact occurs when the element surface penetrates one of the target segment elements TARGE170 on a specified target surface. This element also allows separation of bonded contact to simulate interface delamination. Node locations and the coordinate system for these elements are shown in Figure 3.5 (ANSYS, 2011).

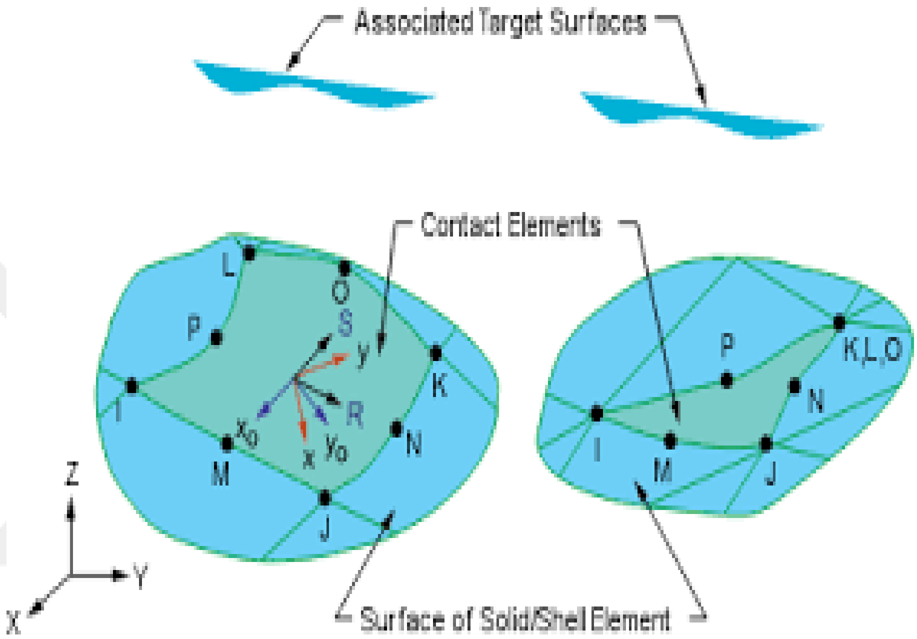

Figure 3.5 CONTA175 and TARGE170 geometry (ANSYS, 2011)

3.3.6 Real constants

The element types that defined in ANSYS needs nodal coordinates, material properties, and geometrical parameters. All element types may not need real constants. Usually, real constants are areas, thicknesses, inner diameters, outer diameters, moments of inertia, etc. If the real constants are not defined and not assigned. ANSYS automatically uses a default value and assigns a number for that particular parameter (Madenci and Guven, 2015).

3.4 Material Properties

3.4.1 Concrete modeling

The PT material components such as concrete, reinforcements, tendons, and contact surfaces are modeled by ANSYS elements. The element types required input properties depending on the analysis types. The material properties may be linear or nonlinear, isotropic, anisotropic or orthotropic. The Solid65 element requires linear isotropic and multilinear isotropic material properties to properly modeling of concrete. Density for the concrete is added in the material model.

3.4.2 Steel modeling

Steel bars and prestressing tendons are slender, they can be assumed to transmit axial force only. Modeling of ordinary steel and prestressed steel in the FEs are much simpler (Ibrahim et al., 2012). The stress-strain relationship for ordinary reinforcing steel bars are illustrated in Figure 3.6, which is bilinear relationship assumed to be elastic-perfectly plastic (Ng and Tan, 2006).

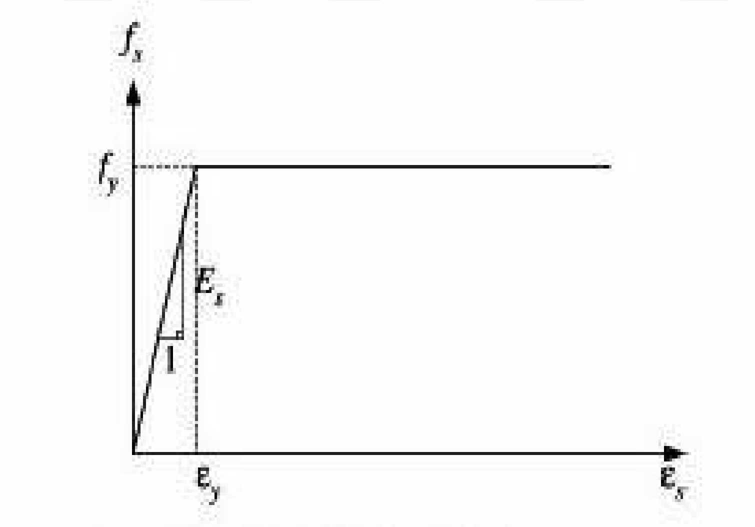

Figure 3.6 Constitutive law for steel reinforcement (Ng and Tan, 2006)

3.4.3 Prestressed tendon modeling

The multilinear isotropic stress-strain relationship for prestressing tendons are represented in Figure 3.7.

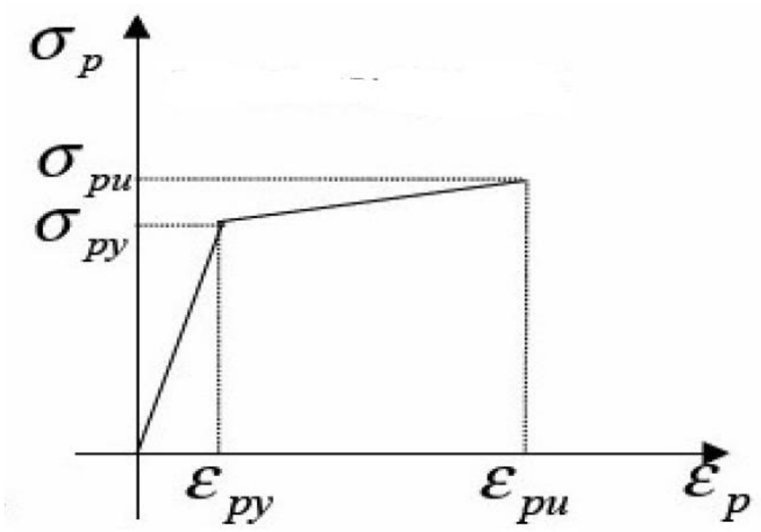

Figure 3.7 Constitutive law for prestressing steel (Ng and Tan, 2006)

3.5 Nonlinear Solutions Methods

The Newton-Raphson method of analysis is used to compute the nonlinear response of PT cantilever concrete models, the application of the loads up to failure is done incrementally for all models and load cases as required by the Newton-Raphson procedure. After each load increment applied, the restart option is used to go to the next step after convergence. The load steps, sub-steps, and loads applied per restart option can be listed in ANSYS. The displacement is the convergence criteria used for the analysis. The load increments increased slightly until subsequent cracking of the beam and failure occurs. Failure of the beam occurs when the convergence fails, when the beams began cracking, convergence for the non-linear analysis is impossible with the default values. The convergence of the solutions for the models was difficult to achieve due to the nonlinear behavior of reinforced concrete. Thus, the convergence tolerance limits increased to a maximum of 5 times the default tolerance limits 5 % for displacement checking, in order to obtain convergence of the solutions (Dahmani et al., 2010). The reinforcing steel reaches to the yielding, then the load increment sizes begin decreasing and displacements are increasing more rapidly (Wolanski, 2004).

3.6 Analyses of Post-Tensioned Concrete Beams

The numerical results are verified by comparison with the experimental results. To validate the proposed nonlinear models, one of the experimentally simply supported prestressed concrete beam experimentally tested by (Hussien et al., 2012) is chosen.

One of their beams was named as the beam B2-70-P-B and tested under static loading up to failure. B2-70-P-B had one strand with a 12 mm diameter and two 10 mm diameter non-prestressed bars, with overall beam geometry dimensions equal to 4400 mm, 160 mm and 340 mm length, width and height respectively. The steel stirrups and non-prestressed steel bars are made of deformed high tensile steel with a yield stress of 470 MPa and ultimate strength of 610 MPa. The yield and ultimate stress of the prestressing steel strands are 1674 and 1860 MPa, respectively. The tendon profiles applied similarly to the bending moment induced from the concentrated loads. The tendons are bonded and grouted with 36 MPa compressive strength. Figure 3.8 shows the dimensions and section details of the prestressed beam specimen. Figure 3.9 shows the concrete mesh. Figure 3.10 shows the reinforcements and mesh of tendon.

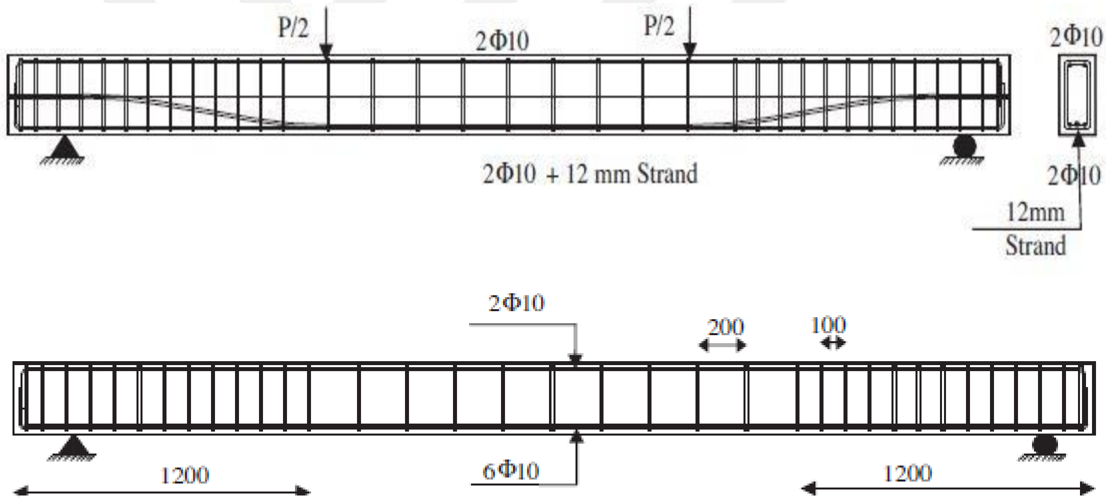

Figure 3.8 Reinforcement and dimension details of prestressed beam B2-70-P-B by (Hussien et al., 2012)

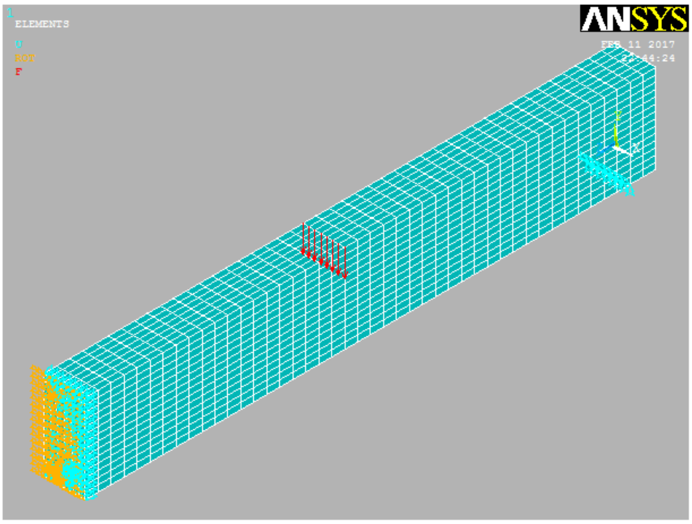

Figure 3.9 Concrete mesh of the half of the beam B2-70-P-B

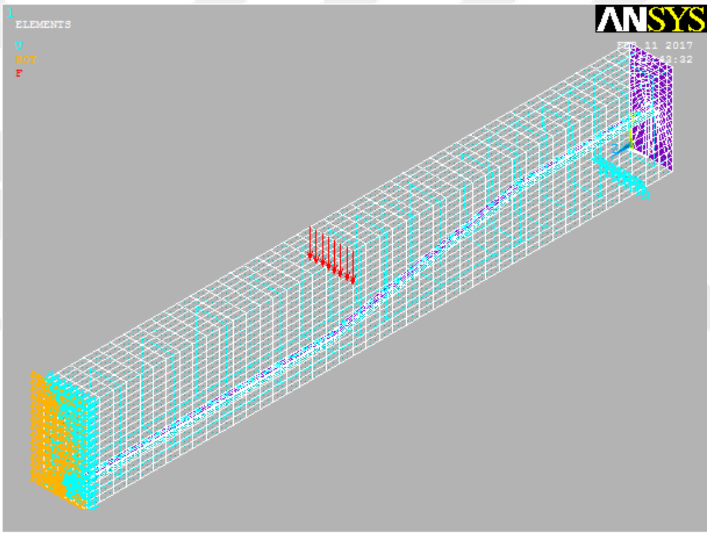

Figure 3.10 Reinforcement and tendon mesh of the half of the beam B2-70-P-B

After modeling and analyzing the experimental model B2-70-P-B by ANSYS program, the results for load-deflection curves are validated and shows good agreement with experimental results as shown in Figure 3.11.

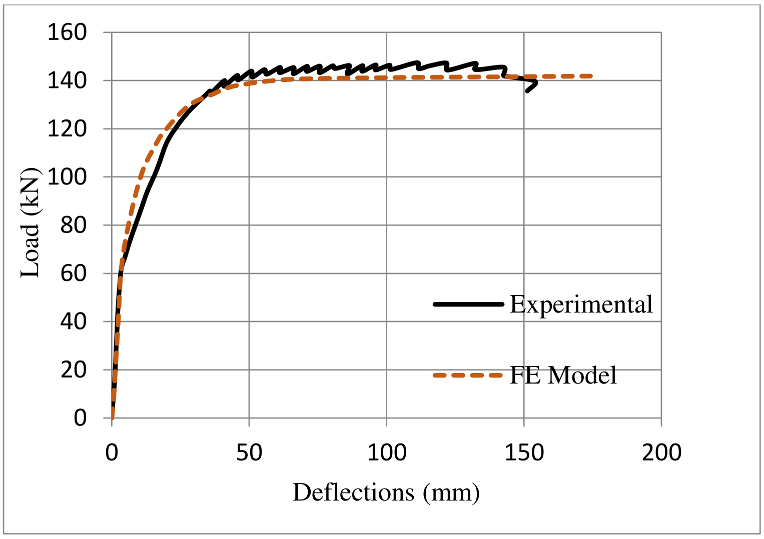

Figure 3.11 Load- deflection curves for the beam B2-70-P-B (Hussien et al., 2012) and FE results

CHAPTER 4

PARAMETRIC STUDY

4.1 Problem Statement

When applying external load on the BPT beams, the change in strain in tendons at any section is equal to the change in strain in adjacent concrete section. The profile of tendons affects the strain and failure loads of the beam members. In PT concrete beams, tendons are classically placed continuously through the supports. Tendon profiles have a great effect on the ultimate load capacity. Different tendon profiles are used to select the optimum profile. In this chapter, numerical results of cantilever beam models have been presented The results include mid-span deflection, end-span deflection, stress and strain in concrete, failure loads, concrete crushing and cracking, and deformed shapes.

Six PT beam models are chosen. The prestressed tendons, beam dimensions, anchorages, load plates and supports are modeled in ANSYS by key points, lines, areas, and volumes. The beam model is 6300 mm. long, with a cross-section of 250 mm width, 450 mm height as illustrated in Figure 4.1. Two longitudinal reinforcements with the diameter of 16 mm are used at bottom and top, stirrups are arranged with the diameter of 10 mm at 300 mm spacing.

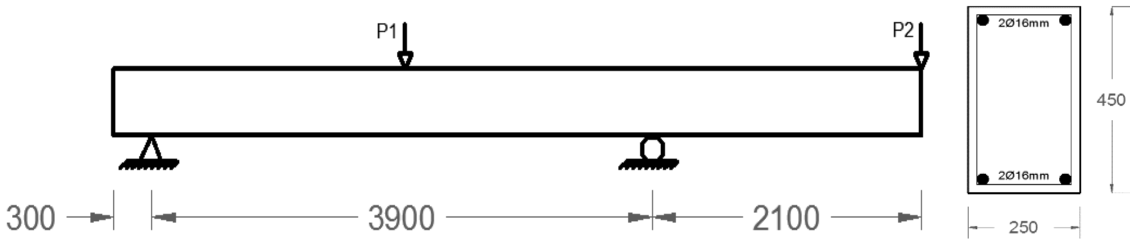

Figure 4.1 Concrete beam dimension and cross-section

The Material properties of concrete, reinforcements, and strands for BPT cantilever concrete beams are shown in table 4.1.

Table 4.1 Material properties of concrete, reinforcements, and strands.

Descriptions	Concrete	Steel plate	Strand
Ultimate compressive strength (MPa) ($f'c$)	30	——	——
Ultimate tensile strength (MPa) (*ft*)	3.8	——	——
Modulus of elasticity (MPa) (E)	30000	200000	206290
Poisson's ratio (υ)	0.2	0.3	0.3
Yield strength (MPa) (f_y)	——	400	1741

Prestressing is a way of counteracting the effect of external loads on a structure by imposing a state of stresses conflicting to the load effects. The most common way to achieve this is by means of tendons, which stressed prior to final loading of the structure. Tendons are typically located near the bottom which positive moments occur and near the top which negative moments occur with the intent to install the cable with the maximum total drape. Different tendon profiles used such as: (without tendons, two tendons at the bottom, two tendons at the middle, two tendons at the top, two parabolic tendons with two draped points, and two parabolic tendons with one draped points). Tendon profiles are shown in Figure 4.2.

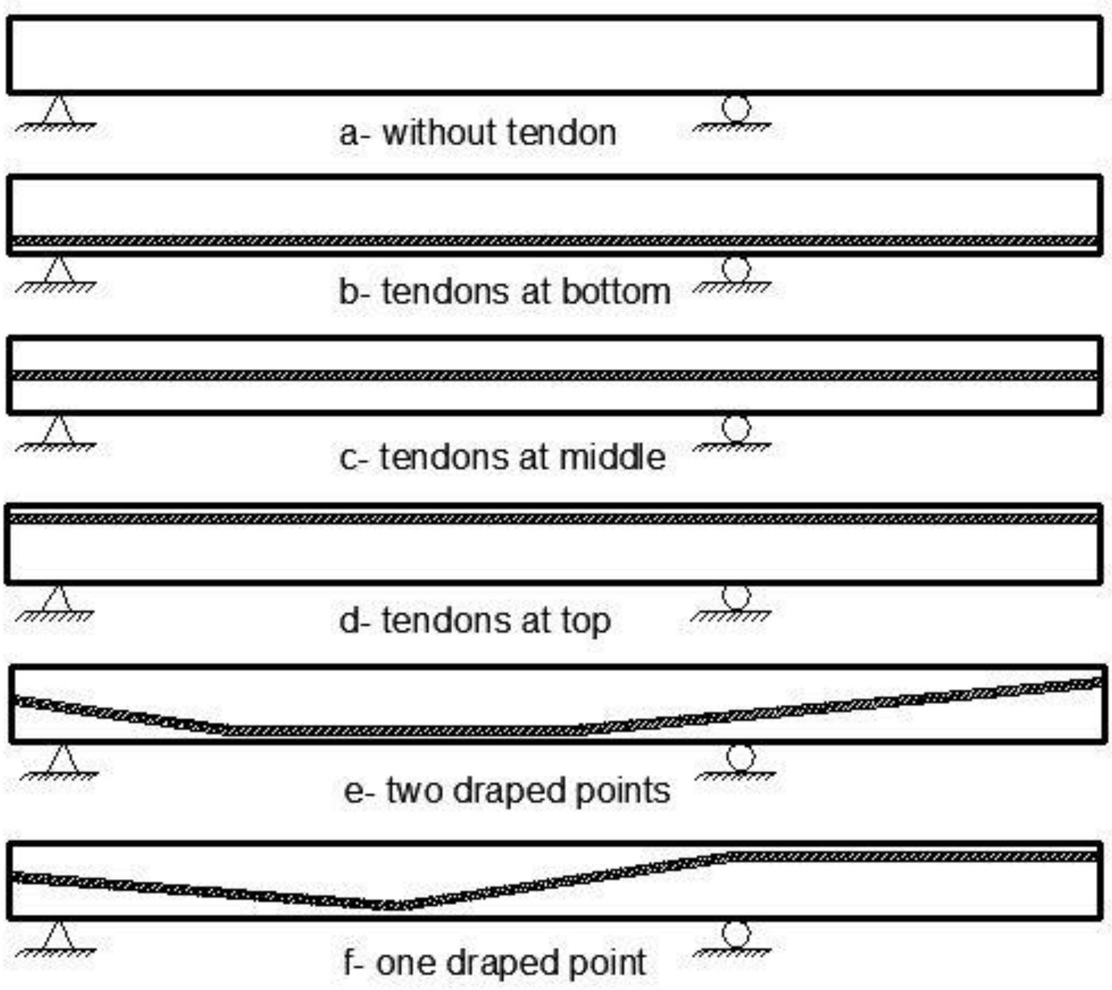

Figure 4.2 Tendon profiles

The boundary conditions include loads and supports are applied to constrain the model to get a unique solution. Boundary conditions must apply at both supports, nodes on both supports must be constrained in the transverse direction. In hinge supports, all the nodes that lie on the middle line of the support are given a constraint value of zero in the Y, and X directions, in roller, all the nodes that lie on the middle line of the supports are given a constraint value of zero in the Y directions. The external loads are applied incrementally up to failure by nodal forces on the steel plates on the top face of the beam.

Three different load cases are applied on the beam models up to failure, load cases and boundary conditions are illustrated in Figure 4.3.

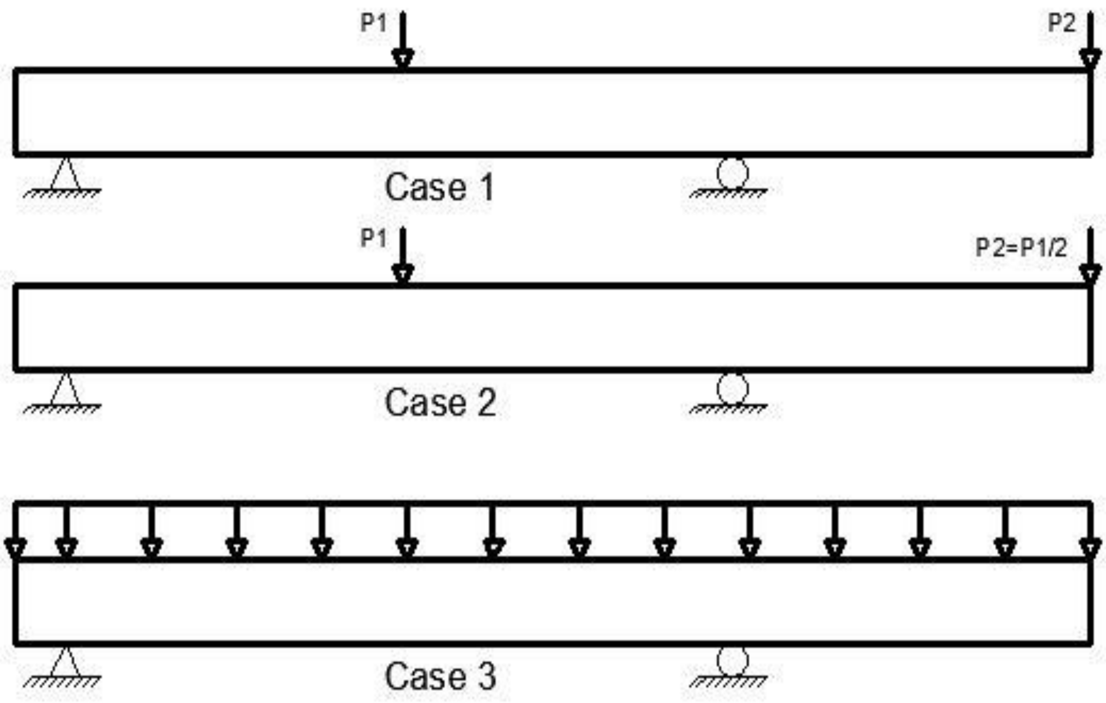

Figure 4.3 Load cases

In this chapter, the most important thing in PT cantilever concrete beams is to find out the effective of tendon profiles on the load-deflections and failure behavior. The nonlinear FEA was achieved to find optimum positions of tendon profiles under different load cases.

In ANSYS, when the solid model is completed, the model is ready to perform meshing. The meshing can perform only after the specification of element types. In the FEA as an initial step, the PT reinforced concrete beams must be divided into a number of small elements This is done by the meshing of concrete beams with appropriate mesh density in directions of (X, Y, and Z) with mesh dimensions (25, 25, 150)-mm respectively, tendons must be meshed with the same dimension of 150-mm in the Z-direction. The mesh density is illustrated in Figure 4.4.

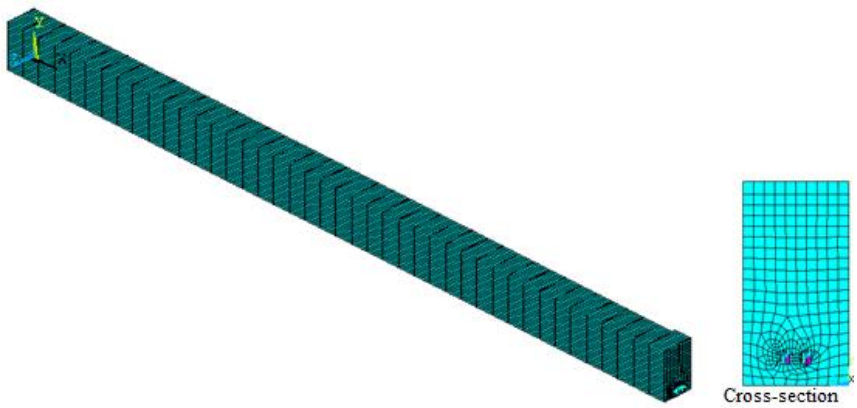

Figure 4.4 Meshing density

ANSYS have the following menu paths for automatic mesh generation after solid model generation: mesh using line elements, mesh using area elements, and mesh using volume elements. ANSYS can control the mesh density of the domains defined by solid model entities, to achieve the desired mesh density.

4.2 Discussion of Results

4.2.1 Load-displacements curves of beams

The ultimate load capacity increased by using parabolic tendon profiles. The beams with one draped tendon profile showed highest ultimate load capacity and stiffer response compared to the beams with straight tendon profiles for all load cases. Because parabolic profiles have the specified values of eccentricities, Eccentricity is a distance between tendons and neutral axis of the member, which produces internal moments that act in opposition to moments induced by external loading. Increasing eccentricity will increase the tendon stress and decrease tensile stresses of the concrete. The parabolic profile is similar to the beam bending moment. The use of parabolic tendons introduces transverse effects to carry more counteract the external loads, with both axial, bending and shear effects. In addition, parabolic tendons give maximum failure load, it is stronger as compared to other beams. Beams with tendons at the bottom gives smaller failure loads and it was very weak. Because in parabolic profiles, the curvature of the cable exerts a force on the concrete to counterbalance the forces that causing tension. The tendons are located with eccentricities to counteract the sagging bending moments due to transverse loads. Consequently, the prestressed beams deflect upwards on the application of prestress. Since the bending moment is the product of the prestressing force and eccentricity, the tendon profile itself will represent the shape of the bending moment diagram.

Figures 4.5, 4.6, and 4.7 shows the load-displacement curves at end of cantilever beams for all load cases that was obtained from FEA, showed that the parabolic tendon profiles give maximum load capacity to failure and it has stiffer response compared to the beams with a straight tendon profile.

Figures 4.8, 4.9, and 4.10 illustrates the load- displacement curves at the middle point of the beams for all load cases. It shows that the ultimate load capacity increased with using parabolic tendon profiles as compared with other undraped profiles. Straight profiles produced the lowest nominal resistance, before yielding no change occur in stiffness. Beam failures of all models were sudden failure above supports due to cantilever effect.

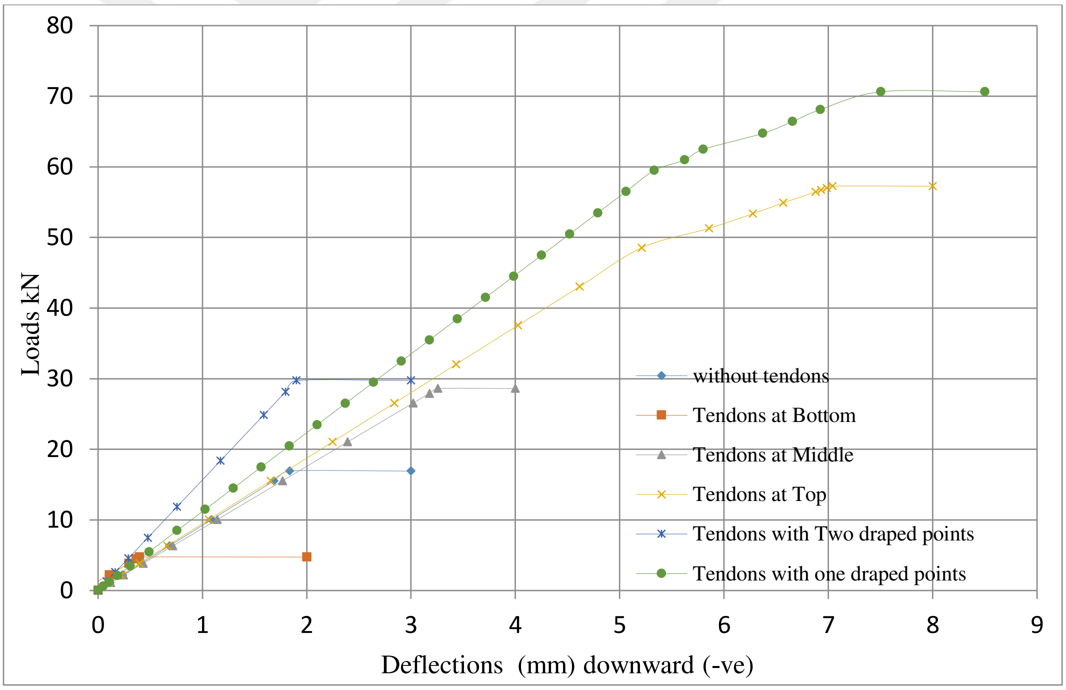

Figure 4.5 Load- displacement curves at the end for load case 1

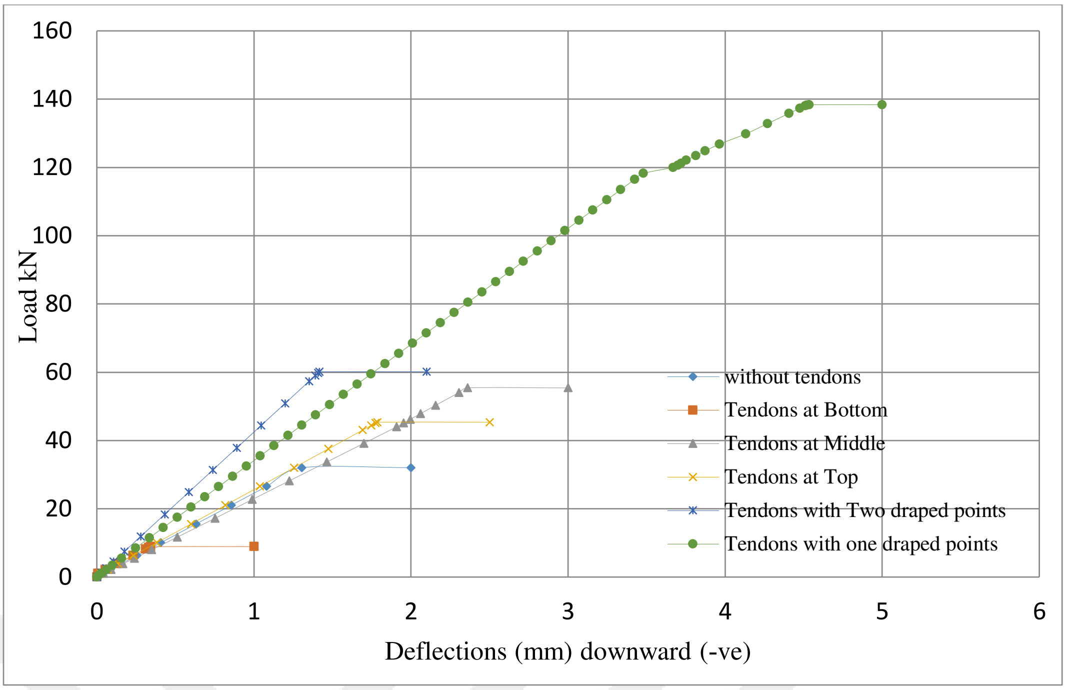

Figure 4.6 Load- displacement curves at the end for load case 2

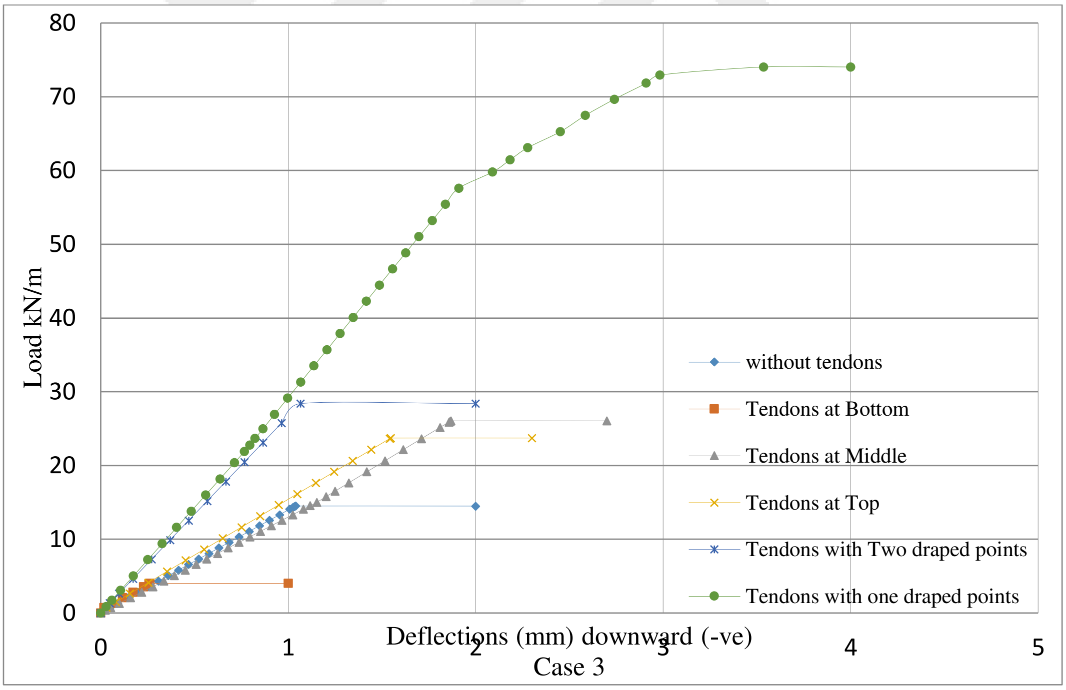

Figure 4.7 Load- displacement curves at the end for load case 3

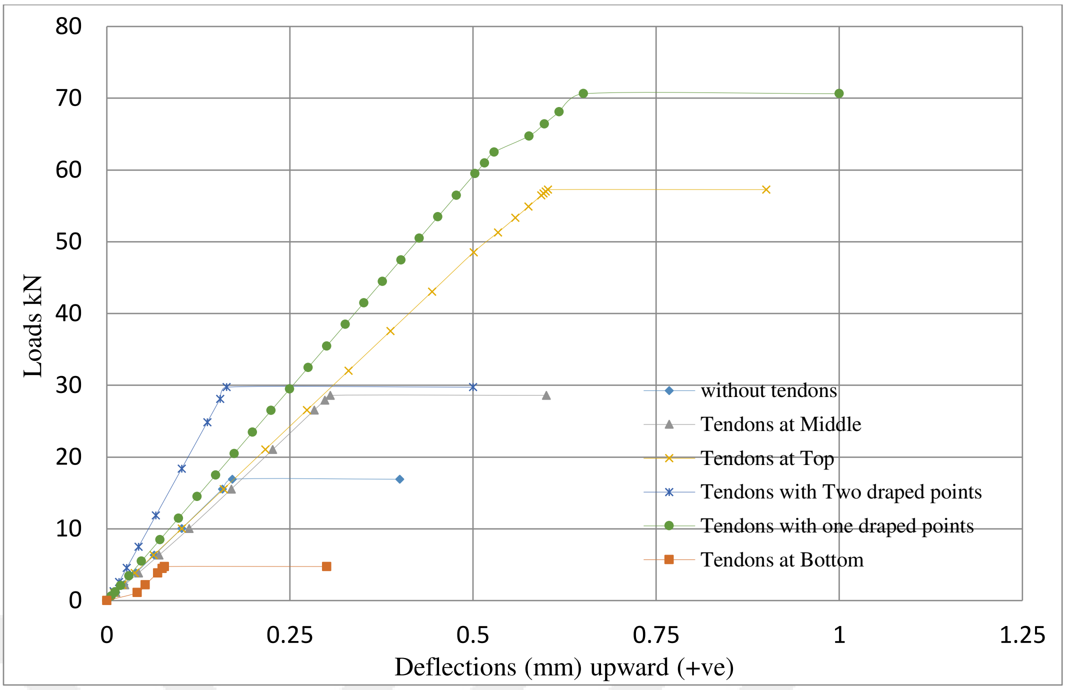

Figure 4.8 Load-displacement curves at middle of simply supported part for load cases 1

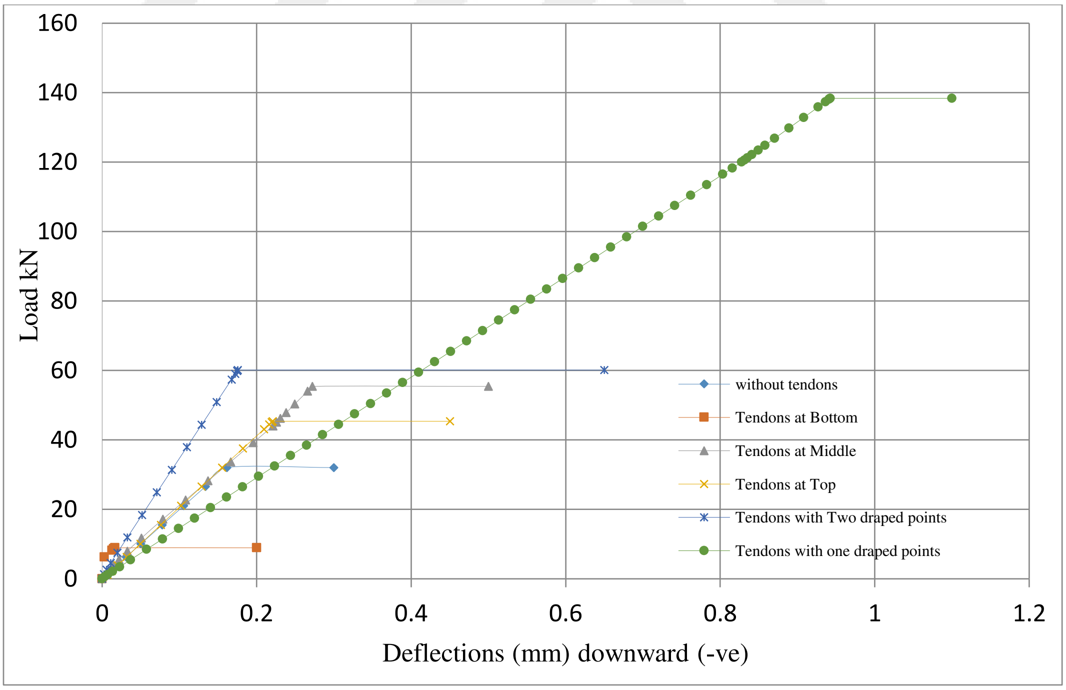

Figure 4.9 Load-displacement curves at middle of simply supported part for load cases 2

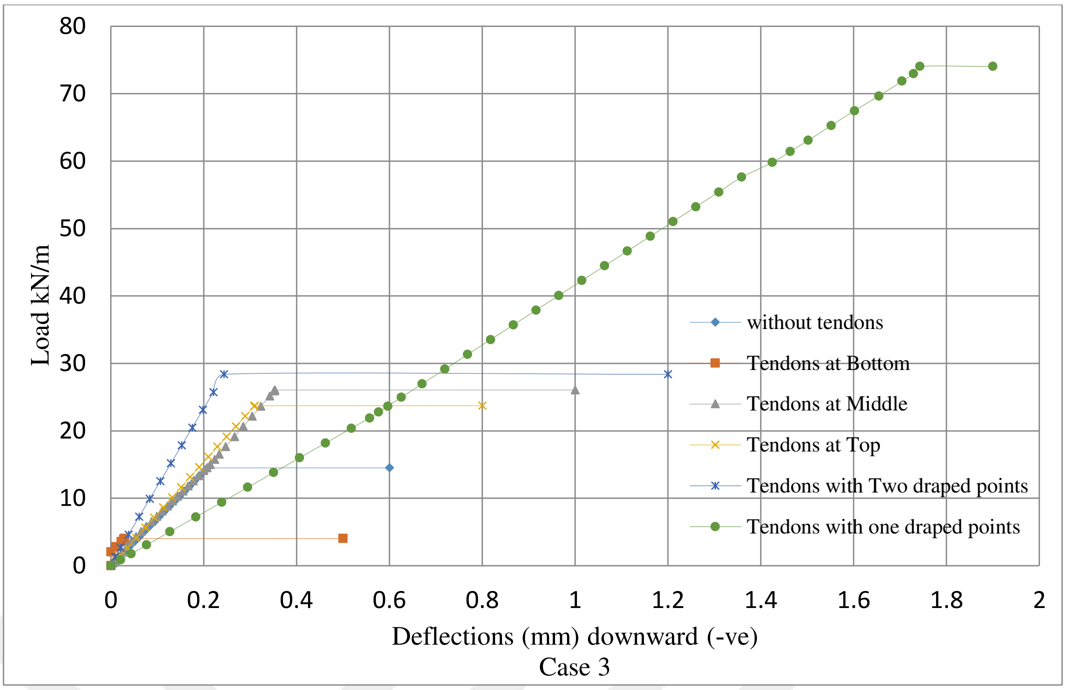

Figure 4.10 Load-displacement curves at middle of simply supported part for load cases 3

4.2.2 Deformed shapes of beams

When loads are applied and increases incrementally on the beam models, the member responses occur in the form of deformation. The initial beam conditions are attainable when the models undergo elastic deformation. Figures 4.11, 4.12, and 4.13 illustrates the deformed shapes for all load cases with constantly applied loads. When loads are applied. Each material follows the constitutive properties considered by their stress-strain relationships. Each material provided the strain energy form to corresponding the deformation response of the members. The behavior of load-deflection relationships is evaluated under increasing loads.

The parabolic tendon profile can undergo more deform without failure. The profile model with one draped tendon profile gives maximum deform and displacements with higher load caring capacity for all load cases due to the profile shapes which is parabolic and it is similar to its bending moment as compared with another profile.

Figures 4.14, 4.15, and 4.16 illustrates the deformed shapes in beam models for all load cases.

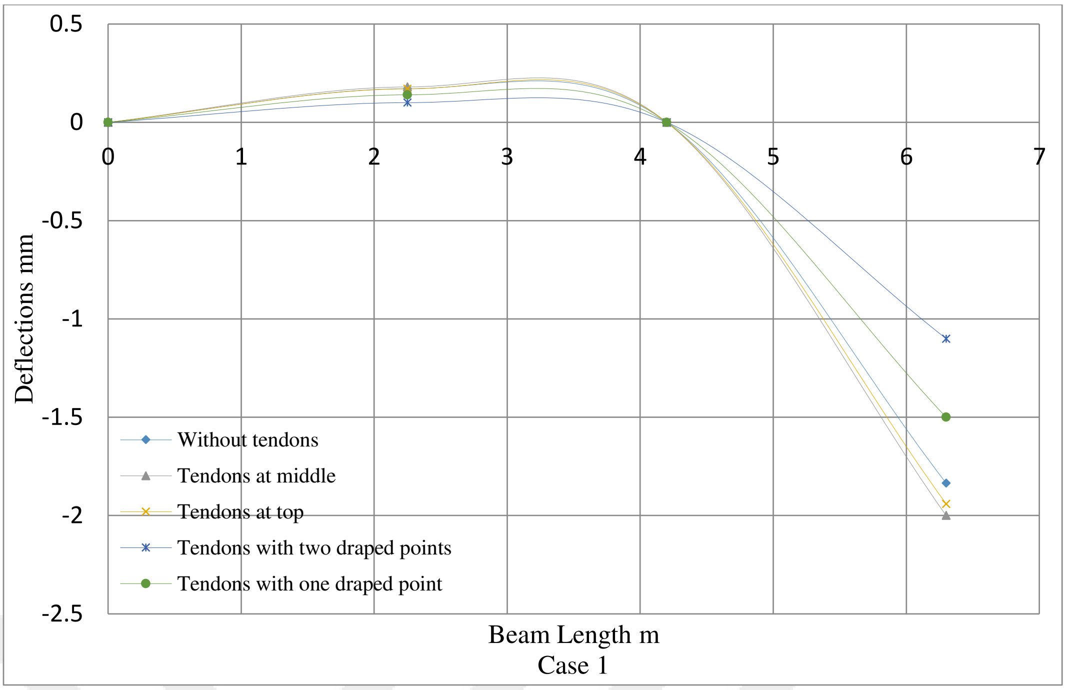

Figure 4.11 Deformed and deflection shapes for load case 1 with constant load 17 kN

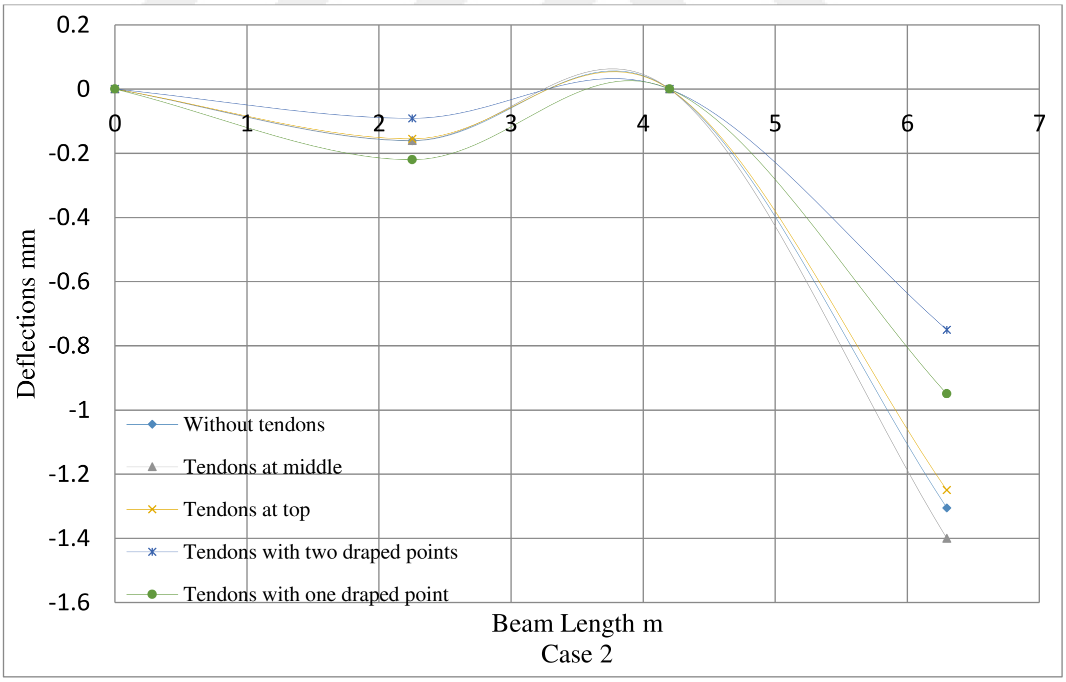

Figure 4.12 Deformed and deflection shapes for load case 2 with constant load 32 kN

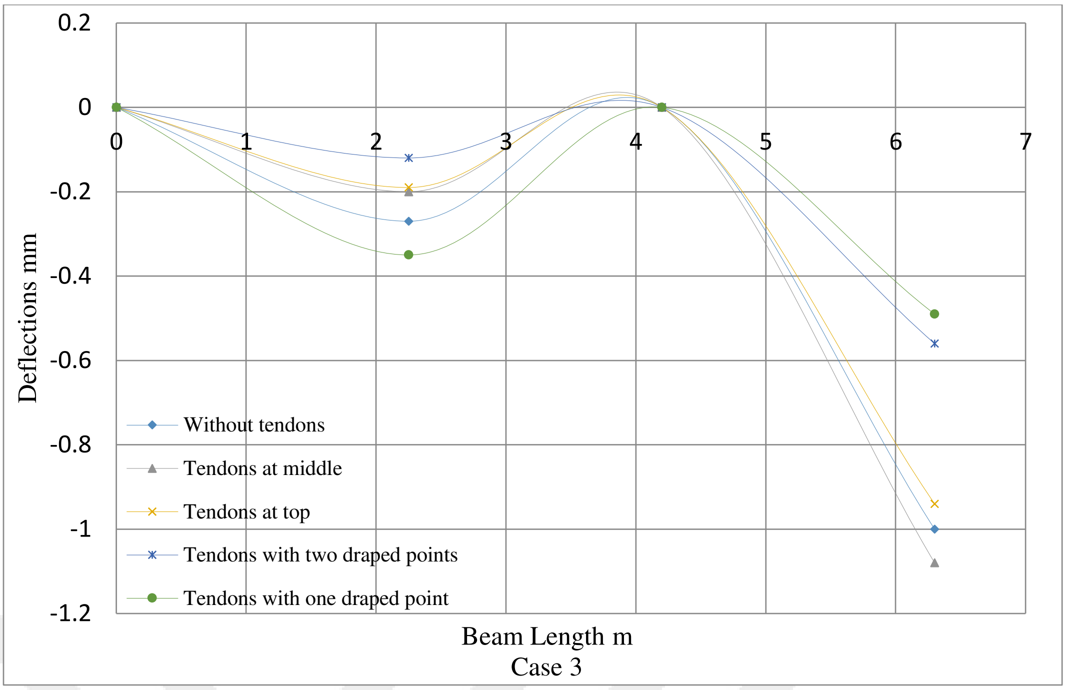

Figure 4.13 Deformed and deflection shapes for load case 3 with constant load 14 kN

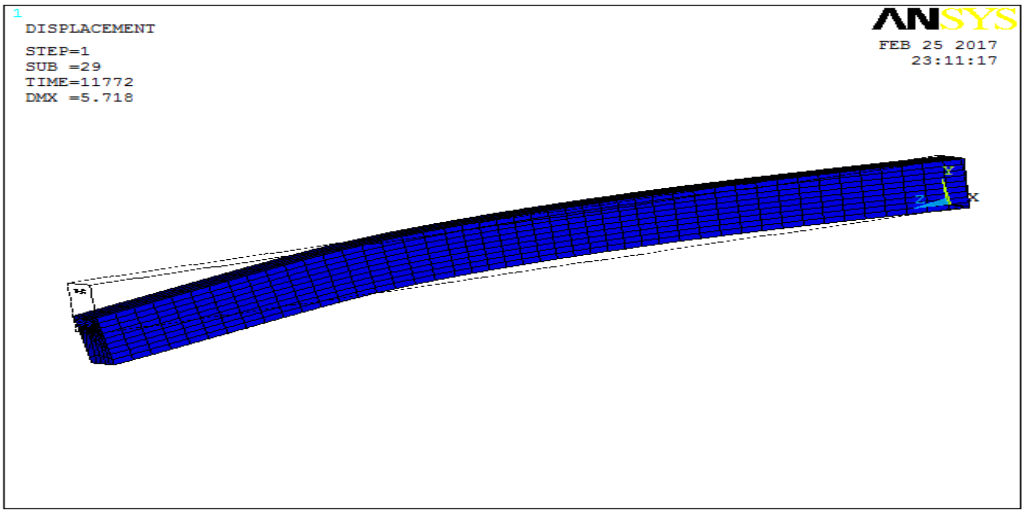

Figure 4.14 Deformed shapes for load case 1

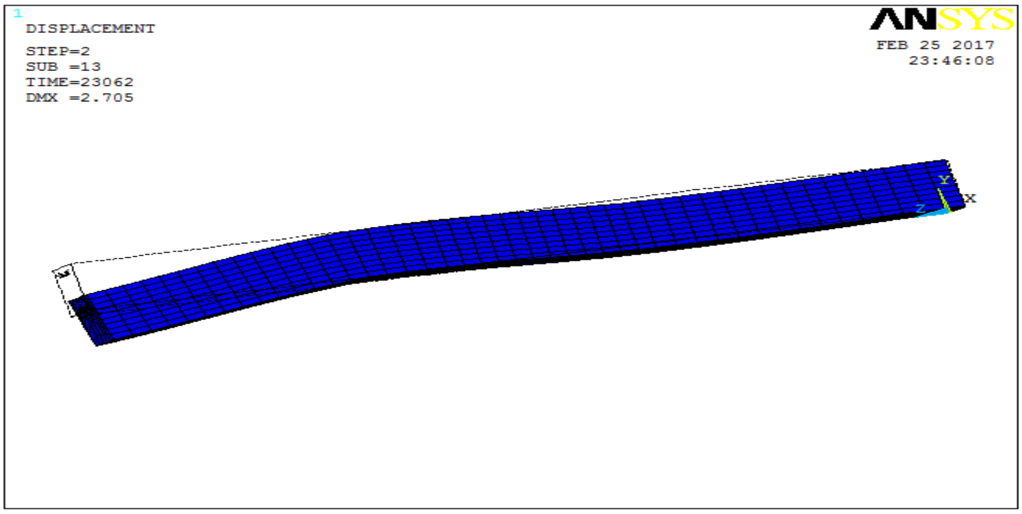

Figure 4.15 Deformed shapes for load case 2

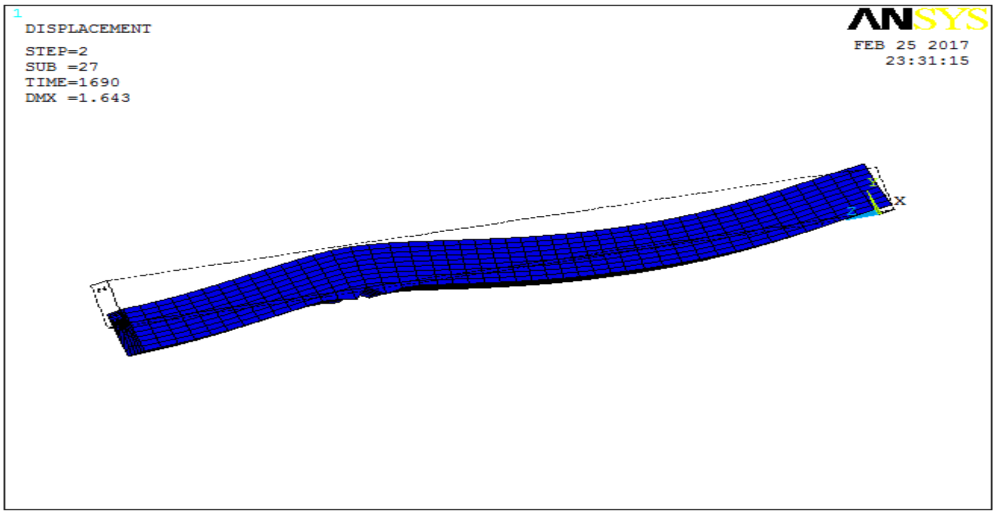

Figure 4.16 Deformed shapes for load case 3

4.2.3 Cracking patterns

The uniaxial tensile stress used for the concrete element is 3.8 MPa. When the concrete cannot withstand and resist additional tension, crack formation occurs and the tensile stress is transferred to the reinforcing steel during the analysis process. As the steel elongates and the bond between the reinforcing steel and its surrounding concrete are damaged, cracks begin to extend and propagate, when the uniaxial tensile stress is over 3.8 MPa. The cracks are initiated in the maximum moment zones, which failure occurs in it and all failure types are concrete cracking suddenly above the support in cantilever part. Figures 4.17, 4.18, and 4.19 shows the crack patterns and failure positions in the concrete of beam models with one draped tendon profiles for all load cases. Figures 4.20, 4.21, and 4.22 shows the typical variation of stress at extreme top fibers of concrete.

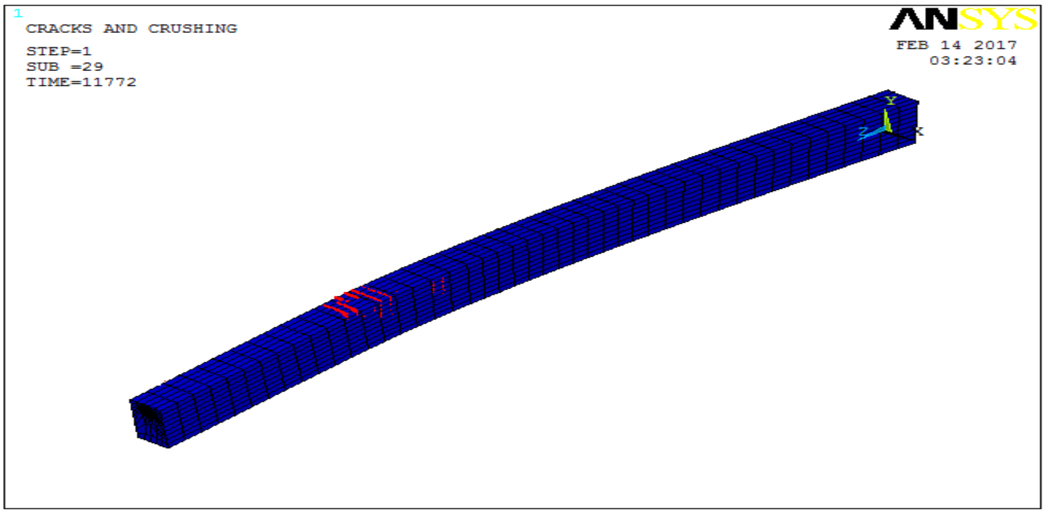

Figure 4.17 Crack patterns and failure in the concrete of beam models with one draped tendon profiles for load cases 1

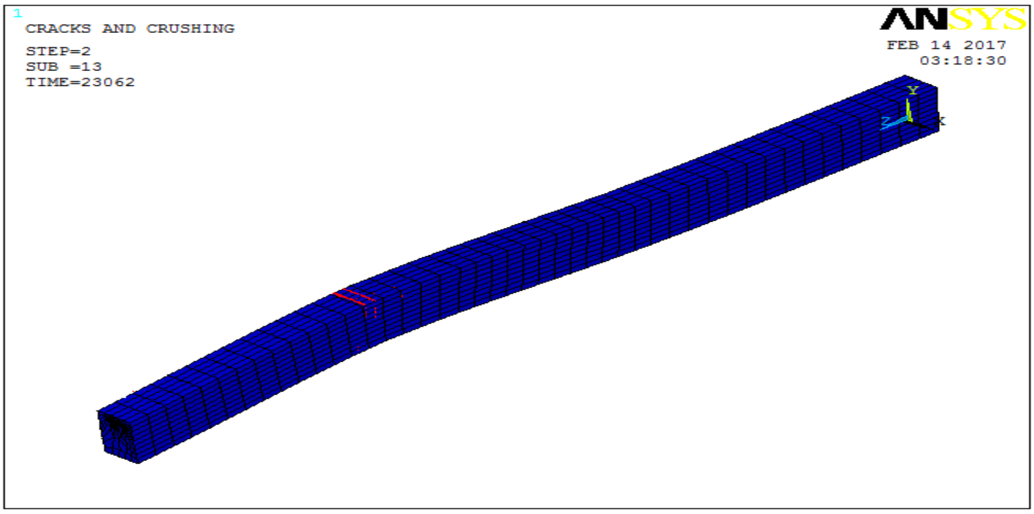

Figure 4.18 Crack patterns and failure in the concrete of beam models with one draped tendon profiles for load cases 2

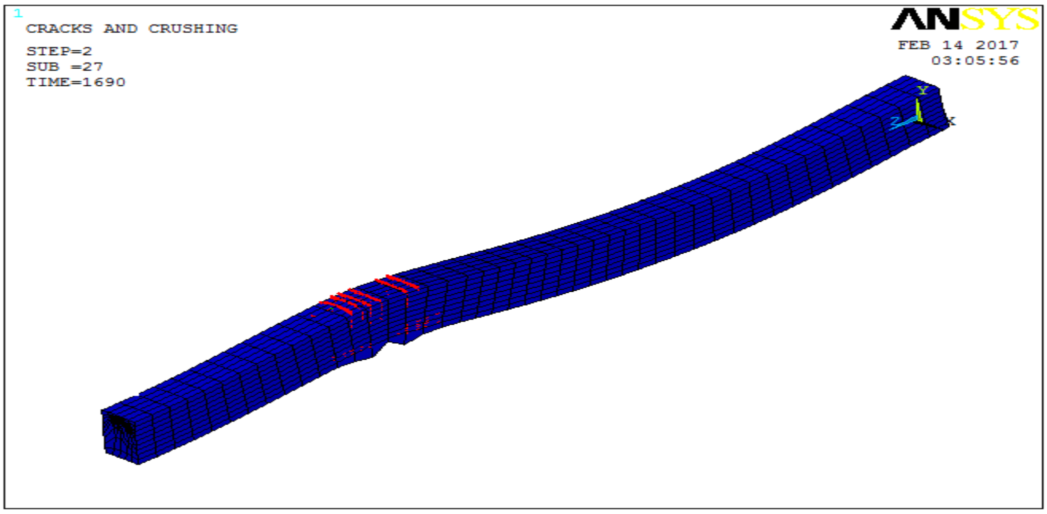

Figure 4.19 Crack patterns and failure in the concrete of beam models with one draped tendon profiles for load cases 3

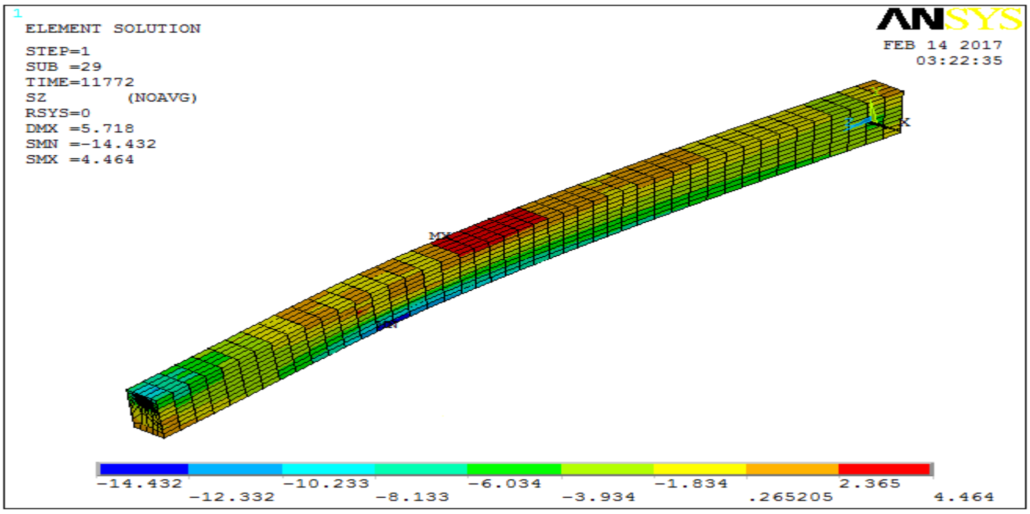

Figure 4.20 Longitudinal stress in the concrete of beam models with one draped tendon profiles for load cases 1

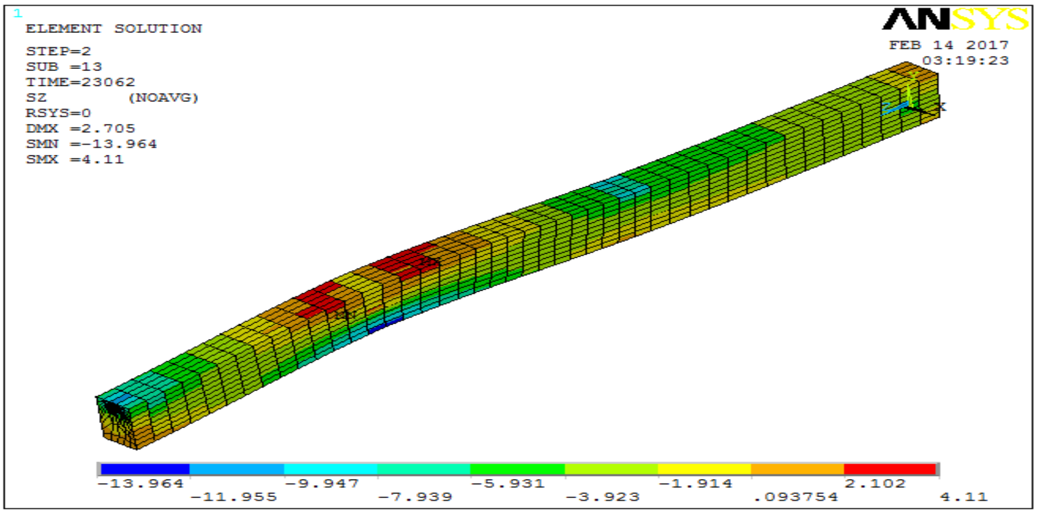

Figure 4.21 Longitudinal stress in the concrete of beam models with one draped tendon profiles for load cases 2

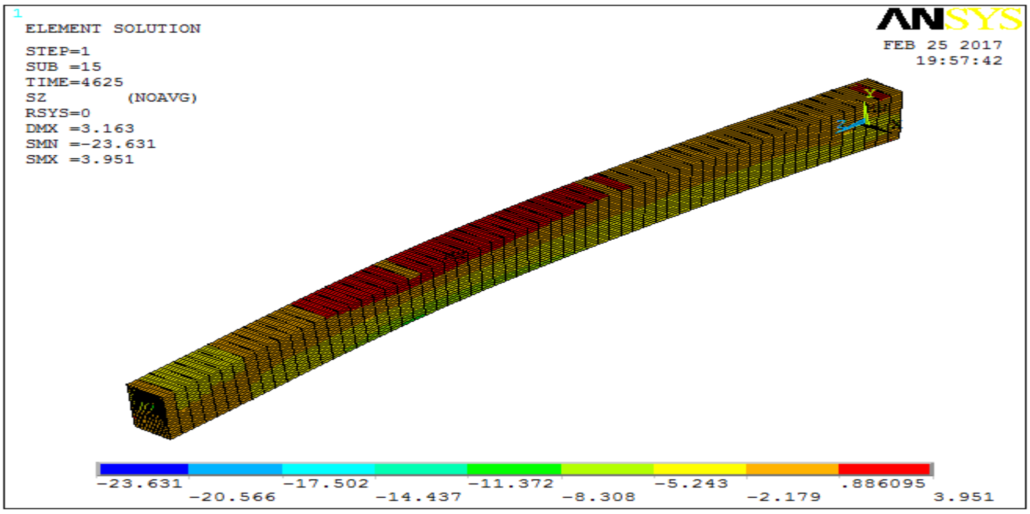

Figure 4.22 Longitudinal stress in the concrete of beam models with one draped tendon profiles for load cases 3

Table 4.2 indicates the failure loads and deflections at the end and middle points of PT cantilever concrete beams for all types of loading. The total deflections are calculated as a resultant of the upward displacement due to PT force and downward displacement due to the gravity and applied loads.

Table 4.2 Failure loads and deflections at the end and middle points.

Loading cases	Tendon profile	Failure loads (kN)	Mid deflections (mm)	End deflections (mm)
Case 1	Without tendons	17.0	0.171	-1.835
	Tendons at bottom	4.7	0.078	-0.396
	Tendons at middle	28.6	0.304	-3.256
	Tendons at top	57.0	0.601	-7.039
	Tendons with two draped points	29.7	0.163	-1.899
	Tendons with one draped point	70.6	0.650	-7.501
Case 2	Without tendons	32.0	-0.161	-1.305
	Tendons at bottom	9.0	-0.016	-0.342
	Tendons at middle	55.0	-0.272	-2.354
	Tendons at top	45.0	-0.220	-1.784
	Tendons with two draped points	60.0	-0.175	-1.417
	Tendons with one draped point	138.0	-0.942	-4.534
Case 3	Tendon profile	Failure loads (kN/m)	Mid deflections (mm)	End deflections (mm)
	Without tendons	14.5	-0.208	-1.039
	Tendons at bottom	4.0	-0.029	-0.263
	Tendons at middle	26.0	-0.353	-1.868
	Tendons at top	23.7	-0.309	-1.546
	Tendons with two draped points	28.4	-0.243	-1.064
	Tendons with one draped point	74.0	-1.742	-3.535

CHAPTER 5

CONCLUSION

5.1 Conclusion

Prestressing is a technic used for constructions like (buildings, bridges, towers and offshore structures…etc.) widely all over the world, due to its efficiency and economy for achieving requirements like long span with small member depth. Prestressing used for flexural strengthening of reinforced concrete structures for improving cracking loads and decrease deflection at service loads. There are two methods for prestressing (pre-tensioning and post-tensioning). In this thesis, a 3-D nonlinear FEM was used to demonstrate the behavior of PT cantilever concrete beams up to failure with different tendon profiles. Numerical analyses package ANSYS program has been used for analysis of nonlinear FE modeling of PT cantilever concrete beams. This thesis is focused on the effect of using different tendon profiles on the flexural behavior of bonded PT cantilever reinforced concrete beams. Six models were studied with different tendons profiles. Failure loads, deflections for all models and load versus deflection relationships were studied. The prestressing force was constant for all models, that was greatly affected the failure loads and deflections.

The accuracy of the analysis was verified by comparisons with the experimental results. The results obtained by using FEA had shown good agreement with the experimental results.

The results showed that the tendon profiles have a great effect on the ultimate load capacity. The ultimate load capacity increased by using parabolic tendon profiles. The beams models with one draped tendon profile showed a higher ultimate load capacity and a stiffer response compared to the beams with straight tendon profiles for all load cases, because parabolic profiles have the specified values of eccentricities, and this profile is similar with the beams bending moment. Also predicted that parabolic tendons profiles in beam models give maximum failure load, it is stronger as compared to other beams. Beams with tendons at the bottom gives small failure loads and it was very weak, because, in parabolic profiles, the curvature of the cable exerts a force on the concrete to counterbalance the forces causing tension. The tendons are located with eccentricities to counteract the sagging bending moments due to transverse loads. Consequently, the prestressed beams deflect upwards on the application of prestress. Since the bending moment is the product of the prestressing force and eccentricity, the tendon profile itself will represent the shape of the bending moment diagram.

The application of load types on each model greatly affects the load-deflection response and failure loads. The distributed loads have greater load capacity.

From Table 2, it can be noted that the distributed loads have greater load capacity. From this table, it can be observed that the failure load in tendons with one draped point profile about 315 %, 331 % and 412 % increases as compared with without tendons profile for the load case1, case2 and case3 respectively.

5.2 Recommendations for Future Study

To follow up this study, the following topics can be suggested:

1- Study the effect of type of suuport on flexure behavior of PT concrete cantilever beams.

2- Study the behavior of PT concrete cantilever beams subjected to fire.

3- Study the optimization of PT concrete cantilever beams..

4- Study the behavior of PT concrete cantilever beams with opening.

5- Study the optimization of positions for one draped tendon profiles to select which point will give you the optimam on PT concrete cantilever beams.

REFERENCES

Abeles, P.W. (1965). An introduction to prestressed concrete, *Concrete Publication Ltd,* **2**, 555.

ANSYS, (2011). ANSYS, Ansys Mechanical APDL Element Reference.

ACI Building Code. (1983). Building Code Requirements for Reinforced Concrete (ACI 318-83), In A. C. Institute, Detroit, Michigan.

Albrifkani, S., Wang, Y. C. (2016). Explicit modelling of large deflection behaviour of restrained reinforced concrete beams in fire, *Engineering Structures,* **121**, 97-119.

AI-Gahtani, A. S., Al-Saadoun, S. S., Abul-Feilat, E. A. (1995). Design optimization of continuous partially prestressed concrete beams, *Computers & Structures,* **55(2)**, 365-370.

Alkhairi, F. M., Naaman, A. E. (1993). Analysis o f Beams Prestressed with Unbonded Internal or External Tendons, *Journal of Structural Engineering,* **119(9)**, 2680-2701.

Allouche, E. (1999). Tendon stressed in continous unbonded prestressed concrete members, *PCI journal,* **44(1)**, 60-73.

Al-Osta, M. A., Isa, M. N., Baluch, M. H., Rahman, M. K. (2017). Flexural behavior of reinforced concrete beams strengthened with ultra-high performance fiber reinforced concrete, *Construction and Building Materials,* **134**, 279-296.

Ariyawardena, N., Ghali, A. (2002). Prestressing with unbonded internal or external tendons: analysis and computer model, *Journal of structural engineering,* **128(12)**, 1493-1501.

Bathe, J. (1996). Finite Element Procedures. U.S.A.: Prentice-Hall Inc.

Berkeley (1967). Slender Prestressed Concrete Columns, *Division of Structural Mechanics,* **67(10)**.

Bums, N. H., Helwig, T., Tsujimoto, T. (1991). Effective Prestress Force in Continuous Post-Tensioned Beams with Unbonded Tendons, *ACI Structural Journal*.

Burns, N. H., Pierce, D. M. (1967). Strength and Behavior of Prestressed Concrete Members with Unbonded Tendons, *PCI Journal,* **12(5)**, 15-29.

Campbell, T. I., Chouinard, K. I. (1991). Influence of Nonprestressed Reinforcement on the Strength of Unbonded Partially Prestressed Concrete Members, *ACI Journal,* **88(5)**, 546-551.

Chakrabarti, P. R., Whang, T. P. (1989). Study of partially prestressed beams with unbonded post-tensioning, *In Structural Design Analysis and Testing*, 189-200.

Chakrabarti, P. R., Whang, T. P., Brown, W., Arsad, K. M., Amezeua, E. (1994). Unbonded Post-Tensioning Tendon and Partially Prestressed Beams, *ACI Structural Journal,* **91(5)**, 616-625.

Colin, M. Z., MacRae, A. J. (1984). Optimization of structural concrete beams, *Journal of Structural Engineering,* **110(7)**, 1573-1588.

Dahmani, L., Khennane, A., Kaci, S. (2010). Crack identification in reinforced concrete beams using ANSYS software, *Strength of materials,* **42(2)**, 232-240.

Dall'Asta, A., Dezi, L. (1993). Nonlinear analysis of beams prestressed by unbonded cables, *Journal of engineering mechanics,* **119(4)**, 720-732.

Du, J. S., Au, F. T., Cheung, Y. K., Kwan, A. K. (2008). Ductility analysis of prestressed concrete beams with unbonded tendons, *Engineering Structures,* **30(1)**, 13-21.

Fanning, P. (2001). Nonlinear Models of Reinforced and Post-tensioned Concrete Beams, *Electronic Journal of Structural Engineering,* **(2)**, 111-119.

Figueiras, J. A., Povoas, R.H. C.F. (1994). Modelling of prestress in non-linear analysis of concrete structures, *Computers & structures,* **53(1)**, 173-187.

Harajli, M. H. (1990). Effective of Span-Depth Ratio on the Ultimate Steel Stress in Unbonded Prestressed Concrete Member, *ACI Structural Journal,* **87(3)**, 305-312.

Harajli, M.H. (1993). Strengthening of Concrete Beams by External Prestressing, *PCI Journal,* **38(6)**.

Harajli, M.H., Kanj, M.Y. (1991). Ultimate Flexural Strength of Concrete Members Prestressed with Unbonded Tendons, *ACI Structural Journal*.

Hopkins, P. M., Chen, A., Yossef, M. (2017). Static and dynamic analyses of insulated concrete sandwich panels using a unified non-linear finite element model, *Engineering Structures,* **132**, 249-259.

Hoyer, E. a. (1939). Contribution towards the Question of Bond Strength, *in Beton und Eisen, Berlin,* **38(6)**, 107-110.

Hussien, O. F., Elafandy, T. H. K., Abdelrahman, A. A., Baky, S. A., Nasr, E. A. (2012). Behavior of bonded and unbonded prestressed normal and high strength concrete beams, *HBRC Journal,* **8(3)**, 239-251.

Ibrahim, A. M. (2010). Parametric Study of Continuous Concrete Beam Prestressed with External Tendon, *Jordan journal of civil engineering,* **4(3)**, 211-221.

Ibrahim, A. M., Mohaisen, S. K., Ahmed, Q. W. (2012). Finite element modeling of composite steel-concrete beams with external prestressing, *International Journal of Civil and Structural Engineering,* **3(1)**, 101-116.

Izzet, A. F. (2016). Effect of High Temperature on the Strain Behavior in Post-Tensioning Concrete Beams by Using Finite Element Method (ANSYS Program), *Journal of Civil Engineering Research,* **6(2)**, 40-46.

Izzet, A. F., Dakel, Z. H. (2015). Behavior analysis of post-tensioning concrete beams exposed to high temperature by using finite element method (ansys program), *Applied Research Journal,* **2(4)**, 220-227.

Jnaid, F., Aboutaha, R. S. (2016). Residual flexural strength of corroded reinforced concrete beams, *Engineering Structures,* **119**, 198-216.

Joshuva, N. R., Saibabu, S., Sakaria, P. E., Lakshmikandhan, K. N., Sivakumar, P. (2014). Finite Element Analysis of Reinforced and Pre-Tensioned Concrete Beams, *International Journal of Emerging Technology and Advanced Engineering,* **4(10)**.

Kachlakev, D., Miller, T., Yim, S., Chansawat, K., Potisuk, T. (2001). Finite element modeling of concrete structures strengthened with FRP laminates*, SPR* **316**.

Kang, T., Huang, Y. (2012). Computer Modeling of Post-Tensioned Structures, *4th International Conference on Computer Modeling and Simulation,* **22**, 41-45.

Kang, Y. J., Scordelis, A. C. (1980). Nonlinear Analysis of Prestressed Concrete Frames, *Journal of the Structural Division ASCE,* **106**(ST2), 445-462.

Kim, K. S., Lee, D. H. (2012). Nonlinear analysis method for continuous post-tensioned concrete members with unbonded tendons, *Engineering Structures,* **40**, 487-500.

Kim, N. H. (2014). Introduction to nonlinear finite element analysis. New York: Springer Science and Business Media.

Kim, U., Chakrabarti, P. R., Choi, J. H. (2010). Nonlinear finite element analysis of unbonded post-tensioned concrete beams, *Challenges, opportunities and solutions in structural engineering and construction, ISBN,* 99-104.

Lees, J. M., Burgoyne, C. J. (1999). Experimental Study of Influence of Bond on Flexural Behavior of Concrete Beams Pretensioned with Aramid Fiber Reinforced Plastics, *ACI Structural Journal,* **96(3)**, 377-385.

Li, G., Liu, D., Yang, Z., Zhang, C. (2017). Flexural behavior of high strength concrete filled high strength square steel tube, *Journal of Constructional Steel Research,* **128**, 732-744.

Litvan, G. G. (1996). Waterproofing of parking garage structures with sealers and membranes, C*onstruction and Building Materials,* **10(1)**, 95-100.

Lou, T. J., Xiang, Y. Q. (2006). Finite element modeling of concrete beams prestressed with external tendons, *Engineering structures,* **28(14)**, 1919-1926.

Lou, T., Lopes, S. M., Lopes, A. V. (2016). Response of continuous concrete beams internally prestressed with unbonded FRP and steel tendons, *Composite Structures,* **154**, 92-105.

Luu, C. H., Mo, Y. L., Hsu, T. T. (2017). Development of CSMM-based shell element for reinforced concrete structures, *Engineering Structures,* **132**, 778-790.

Madenci, E., Guven, I. (2015). The Finite Element Method And Applications in Engineering Using ANSYS, New York: Springer Science Business Media.

Manalip, H., Pinglot, M., Lorrain, M. (1994). Behavior of the Compressed Zone of Reinforced and Prestressed High-Strength Concrete Beams, *Special Publication,* **149**, 209-226.

Mattock, Alan H., Yamazaki, Jun, Kattula, Basil T. (1971). Comparative Study of Prestressed Concrete Beams, With and Without Bond, *ACI Journal,* **68(2)**, 116-125.

Mimoto, T., Sakaki, T., Mihara, T., Yoshitake, I. (2016). Strengthening system using post-tension tendon with an internal anchorage of concrete members, *Engineering Structures,* **124**, 29-35.

Mojtahedi, S., Gamble, W. L. (1978). Ultimate steel stresses in unbonded prestressed concrete, *Journal of the Structural Division,* **104(7)**, 1159-1164.

Moon, J. H., Bums, N. H. (1997). Flexural Behavior of Member with unbonded Tendons I, *Journal of Structural Engineering*, **23(8)**, 1094-1101.

Naaman, A. E. (1982). Prestressed concrete analysis and design*:* fundamentals. New York: McGraw-Hill.

Naaman, A. E., Alkhairi, F. M. (1991). Stress at Ultimate in Unbonded Post-Tensioning Tendons - Part I: Evaluation of the State-of-the-Art, Part 2: Proposed Methodologymber, *ACI Structural Journal,* **88(6)**, 641-651.

Naghipour, M., Nemati, M., Doostdar, H. M. (2010). Experimental Study and Modeling of Reinforced Concrete Beams Strengthened by Post-tensioned External Reinforcing Bars, *International Journal of Engineering,* **23(2)**, 127-144.

Nassif, H, Harajli, M., Khairallah, N. (1999). Externally Prestressed Members: Evaluation of Second-Order Effects, *Journal of Structural Engineering,* **125(10)**, 1151-1161.

Nawy, Edward G. (2011). Prestressed concrete. Pearson Education. 5th ed. New Jersey: Prentice Hall.

Ng, C. K., Tan, K. H. (2006). Flexural behaviour of externally prestressed beams. Part I: Analytical model, *Engineering Structures,* **28(4)**, 609-621.

Ngo, D., Scordelis, A. C. (1967). Finite element analysis of reinforced concrete beams, *In Journal Proceedings,* **64(3)**, 152-163.

Nikolic, Z., Mihanovic, A. (1997). Non-linear finite element analysis of post-tensioned concrete structures, *Engineering Computations,* **14(5)**, 509-528.

Nowak, A. S. (1994). Calibration of the Ontario highway bridge design code, *Canadian Journal of Civil Engineering,* **21(1)**, 25-35.

Nusrath Fahmeen.RP, Satheesh V.SP, Manigandan.MP, Dr.Suresh Babu.SP. (2015). An Overview on Tendon Layout for Prestressed Concrete, *Journal of Innovative Science, Engineering and Technology,* **2(9)**, 944-949.

Park, R., Paulay 1975. Reinforced concrete structures. John Wiley and Sons.

Picard. A., Massicotte. B., Bastien.J. (1995). Relative Efficiency of External Prestressing, *Journal of Structural Engineering,* **121(12)**, 1832-1841.

Rao, S. V., Vegh, L. (1986). Prestressed concrete beams with unbonded tendons, *Indian Concrete Journal,* **60(2)**, 40-44.

Roca, P., Mari, A. R. (1993). Numerical treatment of prestressing tendons in the nonlinear analysis of prestressed concrete structures, *Computers & structures,* **46(5)**, 905-916.

Ozkul, O. (2007). A new methodology for the analysis of concrete beams prestressed with unbonded tendons, *ProQuest*.

Seible, F. Priestley, M., Kirshnan, K. (1990). Strengthening Techniques of Reinforced Concrete Bridges Superstructures, *SSRP-90/06*, **165**.

Shing, P. B., Tanabe, T. A. 2001. Modeling of inelastic behavior of RC structures under seismic loads. *ASCE Publications*.

Srinivasa Rao, P., Mathew, G. (1996). Behavior of externally prestressed concrete beams with multiple deviators, *ACI Structural Journal,* **93(4)**, 387-396.

Tam, A., Pannell, F. N. (1976). The Ultimate Moment of Resistance of Unbonded Partially Prestressed Reinforced Concrete Beams, *Magazine of Concrete Research,* **28(97)**, 203-208.

Tan, K. H., Ng, C. K. (1997). Effects of Deviators and Tendon Configuration On Behaviour of Externally Prestressed Beams, *ACI Structural Journal,* **94(1)**, 13-22.

Tao, X., Du, G. (1985). Ultimate Stress of Unbonded Tendons in partially Prestressed Concrete Beams, *PCI Journal,* **30(6)**, 72-91.

Tavarez, F A. (2001). Simulation of Behavior of Composite Grid Reinforced Concrete Beams Using Explicit Finite Element Methods, (Master's Thesis).

Vacev, T., Bonić, Z., Prolović, V., Davidović, N., Lukić, D. (2015). Testing and finite element analysis of reinforced concrete column footings failing by punching shear, *Engineering Structures,* **92**, 1-14.

Vu, N. A., Castel, A., François, R. (2010). Response of post-tensioned concrete beams with unbonded tendons including serviceability and ultimate state, *Engineering Structures,* **32(2)**, 556-569.

Warwaruk, J., Sozen, M. A., Siess, C. P. (1962). Investigation of prestressed reinforced concrete for highway bridges, part III, strength and behavior in flexure of prestressed concrete beams, *Engineering Experiment Station* **(464)**.

Wolanski, A. J. (2004). Flexural behavior of reinforced and prestressed concrete beams using finite element analysis, Doctoral dissertation, Marquette University, Faculty of the Graduate School.

Yapar, O., Basu, P. K., Nordendale, N. (2015). Accurate finite element modeling of pretensioned prestressed concrete beams, *Engineering Structures,* **101**, 163-178.