COMPARATIVE STUDY ON STRUCTURAL BEHAVIOUR OF BONDED AND UNBONDED POST-TENSIONED BEAM

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UNIVERSITI PUTRA MALAYSIA
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BY

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A Project Report Submitted in Partial Fulfillment of the Requirements of the Degree of Master of Science in Structural Engineering and Construction in the Department of Civil Engineering

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APPROVAL FORM

The project attached hereto entitled, **“Comparative Study on Structural Behaviour of Bonded and Unbonded Post-Tensioned Beam”** prepared and submitted by Nurazuwa binti Md Noor in partial fulfillment of the requirements for the Degree of Master of Science in Structural Engineering and Construction is hereby approved.

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Dedicated to my Family

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ABSTRACT

In this study, a simple computer program are written using FOTRAN 90 to investigate the behavior of simply supported beam constructed with straight tendon which are subjected to three different load cases. Considering the same stresses applied, beam subjected to loading at one third span shows a less deflection than other load cases. Behavior due to the deflection of bonded tendon gave better performance than unbonded tendon. However, beams with larger span-to-depth ratio would require deviators in case of external prestressing to achieve the desired performance. Parabolic and trapezoidal tendon allows the prestressed beam to carry heavier loads because of the balancing effects of the vertical component of the prestressing deflected tendon. Hence it will required less prestressing force at the mid span compared with the force required in the straight tendon.

ABSTRAK

Dalam kajian ini, satu program telah ditulis menggunakan FORTRAN 90 untuk mengkaji kelakuan rasuk prategasan yang ditindaki dengan tiga bentuk beban. Rasuk prategasan yang dikenakan tegasan yang sama akan menunjukkan pengurangan kelakuan lenturan jika dikenakan beban pada satu pertiga rasuk. Kelakuan berkaitan lenturan bagi rasuk prategasan terikat adalah lebih baik berbanding kelakuan lenturan bagi rasuk prategasan tidak terikat. Bagaimanapun, bagi rentang yang mempunyai nisbah L/d melebihi 20, akan memerlukan penyokong pada titik-titik tertentu rentang untuk menghasilkan kelakuan yang lebih baik. Beban yang lebih besar dapat dikenakan terhadap rasuk prategasan yang menggunakan keluli prategasan yang berbentuk parabola, trapezium atau bersudut disebabkan kesan kestabilan pugak. Maka, ia dapat mengurangkan tegasan keluli prategasan yang diperlukan pada tengah rentang berbanding keluli prategasan yang lurus.

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CHAPTER I

INTRODUCTION

1.0 General

Post-tensioning is a method of reinforcing and prestressing concrete, masonry and other structural elements. Simply, concrete and masonry are very strong in compression but relatively weak in tension. In comparison, steel is very strong in tension. Combining steel with concrete or masonry therefore results in a product that can resist both compressive and tensile forces. Further, if concrete is pre-stressed or "squeezed together" with the help of the steel (known as prestressing steel) during the construction phase, its resistance to cracking increases significantly.

External prestressing is a special technique where the first applications date back to more than 60 years. As early as in 1936, low strength prestressing steel is used as external tendons for Aue-bridge in Saxony, Germany which was designed by F. Dischinger before the Second World War [1]. However, during the succeeding years of external prestressing, the advantageous characteristics with internal bonded tendon were discovered. This brings to the 'silent' condition of external prestressing but it did not disappear completely. External prestressing is defined as an arrangement of prestressing tendons outside the section being stressed. The forces are transferred at the anchorage blocks or deviators and those external tendons may be straight or deviated at different points in order to follow the bending moments (see Figure1.1). Whereas, internal prestressing is defined as tendon arrangement within the cross-section of the structures. Internal prestressing can be bonded between the structure and grouted ducts or unbonded between the ducts and tendons.

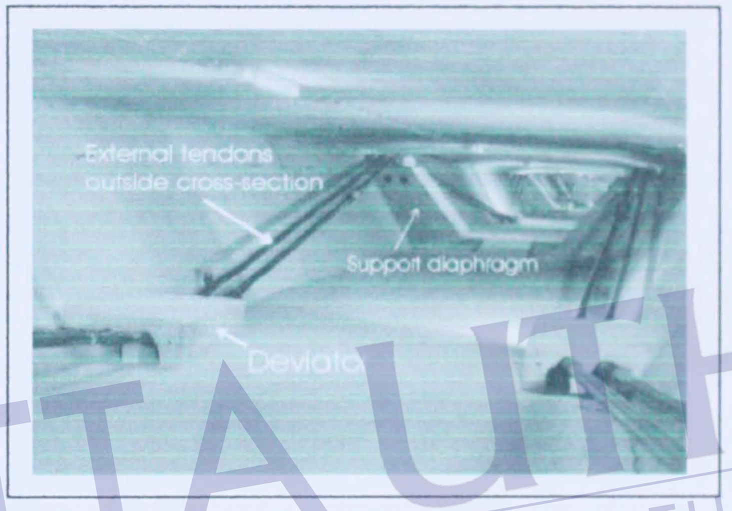


Figure 1.1: Box girder bridge with externally deflected tendons (mysite.wanadoo-members.co.uk/jens/thesis/1_externalPrestress.pdf, 2001)

There are two methods of prestressing: pre-tensioning and post-tensioning [2]. Pre-tensioning, the prestressing steel is stressed at a precast manufacturing facility. Pre-tensioning a concrete member is accomplished by tensioning prestressing strands to the required tensile stress using external jacks and anchors, casting the concrete member around the tensioned strands and, releasing the external strand anchors after the concrete has achieved the required minimum strength. Precompression is induced by the transfer of force through the bond between the prestressing strands and concrete.

With unbonded post-tensioning, the prestressing steel is installed on the job site just before concrete is poured. The prestressing steel is greased and encased in an extruded plastic sheathing to prevent it from bonding to the concrete (Figure 1.2). After the concrete hardens, the prestressing steel is gripped at both ends strands using an external jack, tensioned and anchored to pre-stress the concrete. The strands are typically internal to the member, and may be placed externally. A second anchor is secured against the member and the jacking force is released to transfer the load into the member as a precompression force.

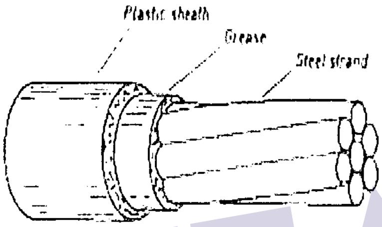


Figure 1.2: Component of an unbonded tendon

Figure 1.3: Component of an bonded tendon

The completed assembly of steel, sheathing and anchors is known as a tendon. Unbonded tendons generally consist of a single strand. With bonded post-tensioning, the prestressing steel is placed in a corrugated metal or plastic duct that has been cast into the concrete. The prestressing steel is usually placed after the concrete has been placed. A bonded post-tensioned tendon typically contains more than one prestressing steel strand and can range from several strands to 55 or more strands in a single tendon, while the anchorage assembly consists of confinement reinforcing steel, bearing plate, anchor head, wedges, and grout cap. The strands can be stressed individually or simultaneously with a monostrand or multistrand hydraulic jack. After stressing, the duct is filled with a low-shrinkage, low-bleed flowable cementitious grout to achieve bond to the concrete member and to protect the prestressing steel from corrosion.

Today, post-tensioning is used for a wide range of applications including office buildings, condominiums, hotels, parking structures, slab-on-ground foundations, ground anchors, storage tanks, stadiums, silos, and bridges. Other applications include post-tensioning in pavement, masonry, bridge decks, seismic walls, and single-family homes [3]. It also can be effectively combined with other structural materials and has been used to strengthen steel, reinforced concrete, masonry, and timber structures, as well as enhance and extend the capabilities of precast, pre-tensioned elements. Examples include spliced precast bridge girders, segmental bridges and hybrid precast moment resisting frame buildings.

One of the most significant reasons for its growth is that post-tensioning allows designers to achieve longer spans with shallower concrete sections, providing owners with the economical advantage of lower floor-to-floor height. This allows architects and engineers to design and build lighter and shallower concrete structures without sacrificing strength. Other key benefits of post-tensioning include functional flexibility, improved deflection and vibration control, crack control and reduced maintenance.

1.1 Problem of Study

Nowadays, prestressing are widely used in the new construction technologies, structures strengthening and repairing. However, due to growing demand for prestressed structures in worldwide including Malaysia, research and laboratory test are progressively continuing. Although various advantages of prestressing have been reported, some question concerning the behavior of bonded and unbonded prestressed concrete structure at ultimate are often arisen in the design practice. This shows that there are still problems in understanding the behavior of prestressed structures especially on unbonded tendon both internally or externally tendon.

An analysis on simply supported beam has been done by Mitchell and Collins in 1990 based on experimental work carried out in 1972 to study the behavior of unbonded straight tendon subjected to load at two third span. Due to these findings, an attractive alternative will be carried out using FORTRAN programming to study the behavior of bonded and unbonded prestressed beam subjected to one point load and uniform distributed load. Based on this analysis, the behavior of prestressed beam subjected to three different load types will be analyses and compare. Additionally, the behavior of different cable profile is also conducted in this analysis.

1.2 Objective of Study

Objective of the study are to:

i. Study the existing theoretical and empirical method of analysis of bonded and unbonded prestressing beam.
ii. Determine the limitation of the methods.
iii. Compare the behaviour of bonded and unbonded prestressed beams, having different cable profile, and load patterns between empirical and theoretical methods.

1.3 Scope of Study

A study on the existing empirical method of bonded and unbonded prestressing beam by previous researchers will be discussed in literature review hence determine the limitation of those methods. The next section deals with the analysis. Analysis will be carried out using suitable software to perform a bonded and unbonded prestressed programmed. Theoretical process is based on the procedure of total strain compatibility method as described by Collins and Mitchell [4]. The scope of this study is limited to:

i. Rectangular of post-tensioning simply supported prestressed beams at ultimate limit state.
ii. Beams with different load path.
iii. Beams with different cable profile.

CHAPTER II

LITERATURE REVIEW

2.0 Introduction

Internal unbonded tendons are used widely in prestressing concrete building structures. In the last decade, external prestressing tendons have also found use in the rehabilitation of structures, where they function primarily as unbonded tendon. In addition to the conventional application of unbonded tendon in post-tensioned construction, they are used in the precast concrete framing system particularly relation to forming connections for precast structures in seismic zones [5].

Unbonded tendons [6] are finding increasing use in the prestressing of modern concrete structures. A tendon normally consists of a seven-wire steel strand, though occasionally a solid bar is used. The tendon is coated with proprietary grease, in order to inhibit corrosion, and encased in a close fitting plastic sheath.

Tendons are positioned within the structural member prior to concreting. Then tendon is stressed once the concrete has hardened. As with all prestressing systems, this imparts a more favorable distribution of stress within the structure, counteracting a proportion of the applied loads [7]. However, unlike other systems, the tendons are not bonded to the concrete and prestressing loads are transmitted to the member by the end anchorages throughout the life of the structure. Due to the bending moment, unbonded prestressing may be straight or deviated at different points whereby the ducts are not bonded directly to the concrete structure and not surrounded by concrete. In unbonded prestressing, there is no strain compatibility between cable and the concrete at every cross-section, thus the increment of cable strain must be evaluated by taking into account the whole structure. For this reason special castings are often used, which are recessed from the face of the member and mortared over for protection after the tendons have been stressed and locked off.

2.1 Technical Features of Unbonded Prestressing

Below are some features on how to describe the characteristic of the unbonded prestressing:

i. Prestressing tendon transferred the exerted forces only to the structures at the anchorages.
ii. Both cable and the structures are not bonded unless the bond is intentionally created at anchorages.
iii. Unbonded prestressing can be combined with any construction material as composite materials, steel, combination of steel and concrete, and other modern plastic material. This can considerably widen the scope of the post-tensioning applications.

iv. In case of external prestressing, it is possible to restress, distress and exchange any external prestressing cable due to the absence of bond, if allowed by structural detailing.

2.2 Prestressing System and Types of Material

Several prestressing systems have been approved by the authorities and on the market. In addition almost any producer is developing new system and will extend the variety on the market. Figure 2.1 shows a few of prestressing system available. Based on VSL International Limited, a post-tensioning tendon consists of the following element:

i. Prestressing steel as tensile members
ii. Mechanical end anchorage devices
iii. Corrosion protection systems
iv. Deviators in the case of deflected tendon (external prestressing).

2.2.1 Prestressing Steel

Most material standards for prestressing steel distinguish between smooth and ribbed bars, wires and strands. Around 1993, the majority of post-tensioning tendon consists of strand bundles with wedge type anchorages and no longer of wire or bars with positive end anchorages. However, it is suggested that today the total built-in tonnage of steel consists of 75% strands, 15% wires and 10% bars where strands and wires can be applied more or less universally.

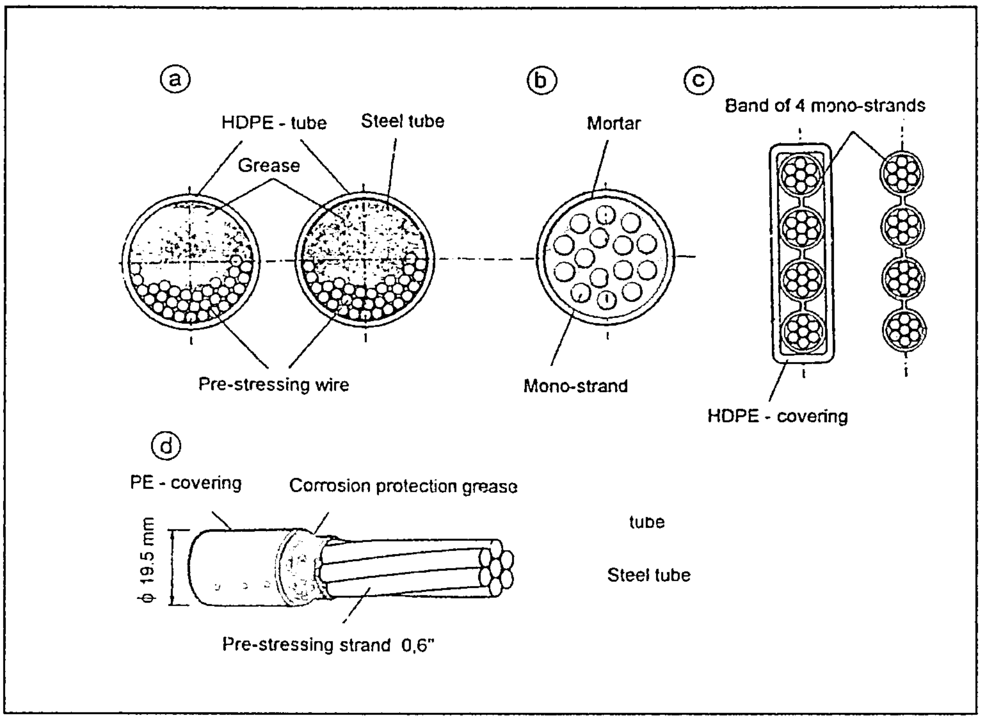
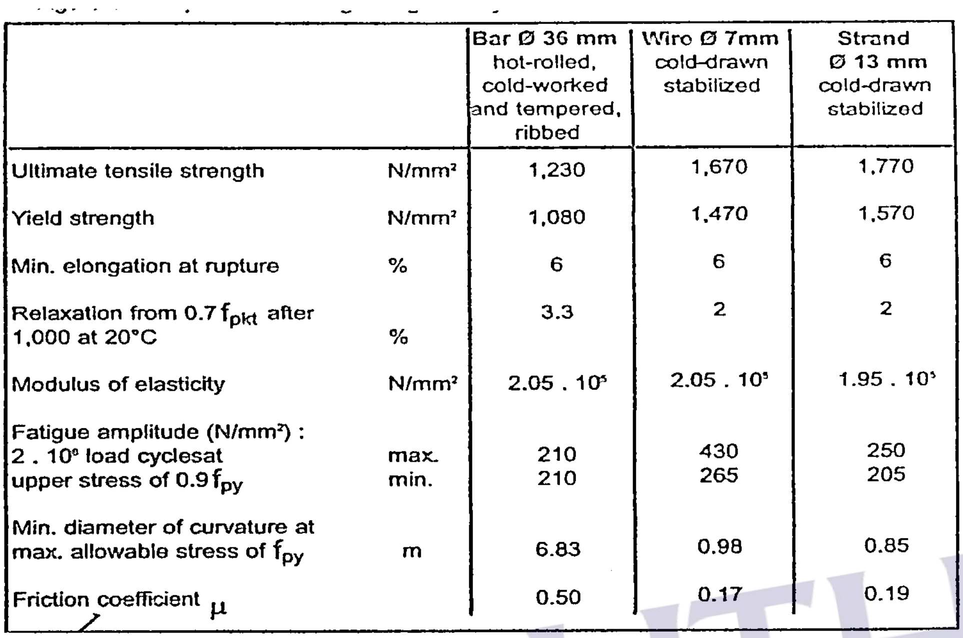


Figure 2.1: Types of tendons

The question arises why strands have taken such a large share? The excellent groutability and the favorable ton per force price of the strands may be emphasized and this trend is continuing. Based on Federal Republic of Germany, Table 2.1 shows the comparison of various characteristics of the most commonly used prestressing steel in Germany.

a. Tendons Consisting of High Strength Bars

These tendons are suitable for short length structure. The tendons consist of smooth or threaded bars provided with corrosion protection system. Several bars can be bundled and anchored at one plate in case of high forces. The most common type is to envelope the bars with steel or PE-pipes filling the voids with cement grout before or after stressing. The main advantages are the easy handling due to the low weight of the element and the stressing force due to the anchor nuts and their low slippage.



		Bar Ø 36 mm hot-rolled, cold-worked and tempered, ribbed	Wire Ø 7mm cold-drawn stabilized	Strand Ø 13 mm cold-drawn stabilized
Ultimate tensile strength	N/mm^2	1,230	1,670	1,770
Yield strength	N/mm^2	1,080	1,470	1,570
Min. elongation at rupture	%	6	6	6
Relaxation from 0.7 f_{pkt} after 1,000 at 20°C	%	3.3	2	2
Modulus of elasticity	N/mm^2	2.05 . 10^5	2.05 . 10^5	1.95 . 10^5
Fatigue amplitude (N/mm^2) : 2 . 10^6 load cyclesat upper stress of 0.9 f_{py}	max. min.	210 210	430 265	250 205
Min. diameter of curvature at max. allowable stress of f_{py}	m	6.83	0.98	0.85
Friction coefficient μ		0.50	0.17	0.19

Table 2.1: Characteristics of prestressing steels according to German documents (VSL International Ltd)

b. <u>Tendons Consisting of Wire or Strands</u>

Tendons with parallel wires or strands normally consist in their free length of three components which are:

i. Tensile element: bar, sheathed or coated wires or strands.

ii. Filling material: cement grout or corrosion protection fillers such as grease, paraffin and petrolatum.

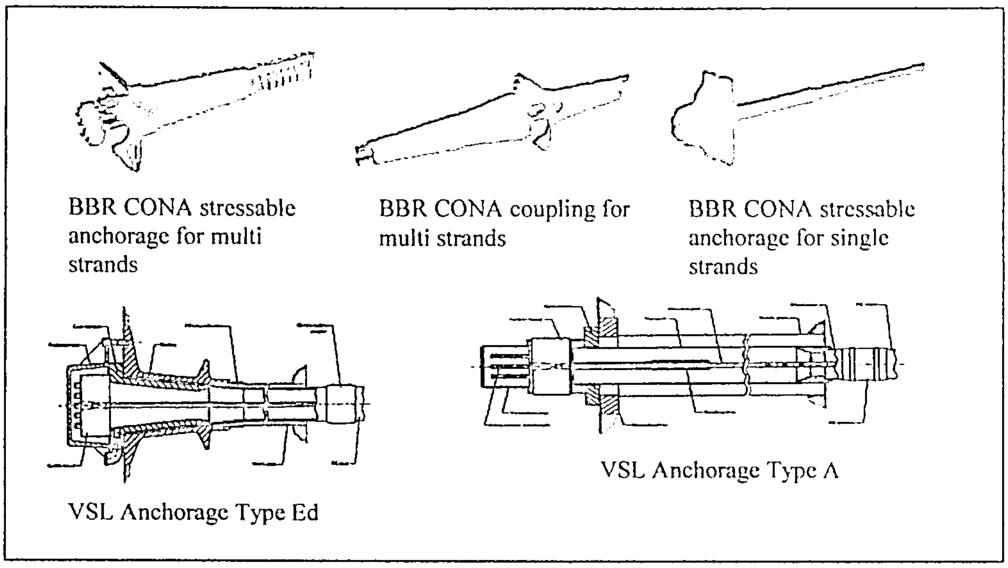
iii. Sheathing: HDPE, glass fiber reinforced plastics or steel.

Each material has its own advantages. A system used with epoxy coated strands filled with epoxy is used to avoid humidity. For individually protected strands used as tensile elements, enveloped by grease or wax and PE-jacket, bleeding of the grease after hardening of the surrounding grout is not possible. The advantage of this solution lay in the design appropriate to the material characteristics which mean the failure of one element does not lead to the complete breakdown of the corrosion protection.

2.2.2 Tendon Anchorages

For years until today, research and technologies has brought to the development of various types of anchorage such as VSL anchorage, BBRV anchorage, PBL anchorage and others (see Fig. 2.2). These anchorages are used widely in internal prestressing system and the same application was applied to the unbonded prestressing system. Unbonded tendons were anchored with the same mechanical devices as those used for external tendon at the end or any point of structure depending on type of structures and requirements.

Anchorage points have a much higher importance in unbonded prestressing structures because this is the only point where the tension from the strands is contained [8]. Thus, it is important to note that anchorages for unbonded tendons must withstand the tendon force or any potential subsequent increase during the lifetime of a structure from construction through all stages of utilization. Also, the performance and reability of end anchorages must be fully effective at all time.



BBR CONA stressable anchorage for multi strands

BBR CONA coupling for multi strands

BBR CONA stressable anchorage for single strands

VSL Anchorage Type Ed

VSL Anchorage Type A

Figure 2.2: Types of Anchorage

2.2.3 Corrosion Protection

Unbonded tendons occur when the tendons are lubricated to facilitate tensioning and intentionally left ungrouted. When grout fails to bind the tendons to the concrete properly, the members are also considered unbonded. Prestressing tendon will be exposing to the environment and needs careful protection against the various types of corrosion attack. BS 8110: Part 1:1985 listed the exposure condition as shown in Table 2.2.

If the tendons are not grouted then an alternative method of providing corrosion protection has to be employed. Recommendations for the corrosion protection of unbonded tendons were published by the FIP in 1986 which are as below:

Environment	Exposure Condition
Mild	concrete surfaces protected against weather or aggressive condition
Moderate	Concrete surfaces sheltered from severe rain or freezing whilst wet Concrete subject to condensation Concrete surfaces continously under water Concrete in contact with non-aggressive soil
Severe	Concrete surfaces exposed to severe rain, alternate wetting and drying or occasional freezing or severe condensation
Very Severe	Concrete surfaces exposed to sea water spray, de-icing salts, corrosive fumes or severe freezing condition whilst wet
Extreme	Concrete surfaces exposed to abrasive action, e.g. sea water caryying solids or flowing water with pH less or equal 4.5 or machinery or vehicles

Table 2.2: The exposure condition (BS 8110: Part 1: 1985)

a) The type of protective material to be used (a special grease) and its method of application
b) The sheathing to be used- a high density seamless plastic tube extruded over the greased tendon, continuous for the full length of the tendon and sealed up to the anchorages so that it is completely waterproof
c) Sealing the ends of the tendon and protecting the anchorages
d) Examination and repair of damaged sheathing
e) Standard tests for the protective material.

There are several aspects to which attention must be paid in both design and construction and in addition, a good workmanship and adequate material are needed for corrosion protection. Many different solutions has been taken out based on experience and research such as zinc coating which has been used in France, polymer coating has been developed in United States and protective sheathing [9]. *Nik Winkler and George Zenobi* in their report states that for the corrosion protection prestressing tendons there exist a variety of organic filling material such as grease, wax or paraffines and some resin based filling material. However, its normally do not offer an active corrosion protection as cement grout thus considerable improvement either by galvanizing the prestressing tendon or by adding a corrosion inhibiting filler such as cement.

Since post-tensioning was first used domestically in 1949, the industry has seen many technological advances, including seven-wire strand, low relaxation strand, improved analysis techniques and design software, the use of bonded tendons, extruded sheathing, encapsulated anchors, and plastic duct systems, as well as the development of pre-packaged, non-bleed grouts. However, one of the greatest advancements is the progress made during the last decade in plastic duct corrosion protection.

2.3 Advantages and Disadvantages

Unbonded tendons have certain advantages compared to bonded tendons. This includes [10], [11], [12];

a) Tendon is not bonded to the structure it is able to move in order to redistribute any local high stresses, e.g. those caused in a building where one floor is heavily loaded and other floors are not loaded or where a particular part of a floor is overheated.
b) If a unit is damaged or cracked by impact or overload it will close up again on removal of the overload.

c) The redistribution of stress the local deflection can be less than with a bonded tendon.

d) Because an unbonded tendon is of small overall diameter, it follows that the centroid of the steel can be placed nearer to the face of the concrete than is possible with a bonded tendon, so that a larger lever arm is provided.

e) Unbonded tendons lend themselves to simpler prefabrication and have lower friction values. The delays caused by injecting cement grout and awaiting hardening are avoided, so the use of unbonded tendons often leads to an increased construction speed.

f) Thinning web thus reduce the superstructure self-weight.

g) Easy concreting of thin cross-section and vibration; there is no weakening of the compression area due to ducts.

h) Reduction of on-site labors.

However, post-tensioned members with unbonded tendons are inferior to those with bonded tendons in terms of both service and ultimate load behaviour: cracks are wider and ultimate bending and shear capacities are less. Bonded systems offer a significant design advantage which leads to life-cycle savings. The key design feature of bonded systems is the hardened grout that locks the movement of the post-tensioning strands to that of the surrounding concrete. Hence, the force in a bonded strand is a function of the movement of the surrounding concrete. This concept of strain compatibility allows for a more efficient use of the prestressing steel and a reduction in the amount of supplemental mild steel.

Another design advantage of bonded post-tensioning is the inherent capacity to provide resistance to progressive collapse [13]. This may be especially important in the event of localized blast loading. Like mild steel reinforcement, a bonded post-tensioning tendon has a relatively short development length. In the event that an anchorage fails or a strand is severed, the loss of tendon force is localized. The remainder of the tendon would retain its force at the development length, away from the failure point, and would remain functional. This functionality can be used in the design phase when planning for alternative load paths.

Bonded systems also offer several practical benefits, such as a reduction in the amount of mild steel needed, particularly at the top of slabs. Reducing mild steel is especially important, as most maintenance costs are due to repairs associated with spalled concrete and corroded rebar. Another benefit is complete encapsulation; the strands are fully protected by cementitious grout, plastic duct and surrounding concrete. The bonded systems also offer more flexibility in terms of structural modification for stairwell openings, utility access and future expansion.

2.4 Flexural analysis

2.4.1 Typical loading history and corresponding stress applied on prestressed tendon

Differ from reinforced concrete members, the external dead load and partial live load are applied to the prestressed concrete member at varying concrete strength at various loading stages.

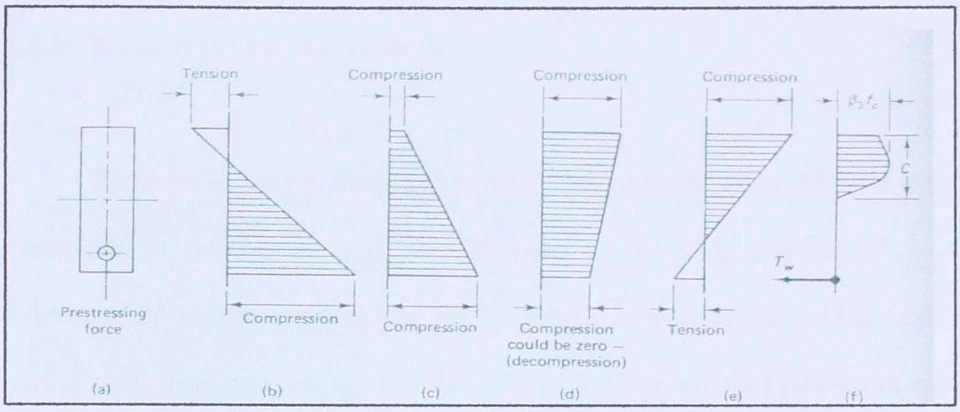


Figure 2.3: Flexural distribution throughout loading history. (a) Beam section. (b) Initial prestressing stage. (c) Self-weight and effective loading history. (d) Full dead-load plus effective prestress. (e) Full service load plus effective prestress. (f) Limit state of stress at ultimate load underreinforced beam (Nawy E.G., 1989)

A typical loading history and corresponding stress distribution across the depth of the critical section are shown in Figure 2.3, while a schematic plot of load versus deformation is shown in Figure 2.4 for the various loading stages from the self-weight up to rupture.

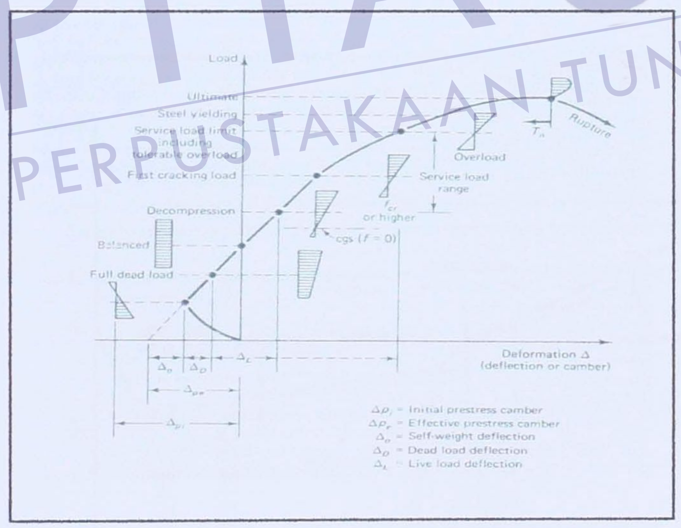


Figure 2.4: Load-deflection curve of typical prestressed beam (Nawy E.G., 1989)

2.4.2 Stresses in steel due to loads

Prestress in steel is measured during tensioning operation then the losses are computed, in prestressed concrete. In order to get clear understanding of the behaviour of prestressed-concrete beam, it will be interesting to first study the variation of steel stress as the load increases. For the midspan section of a simple beam, the variations of steel stress with load on the beam are shown in Figure 2.5. It shows not only the load-deflection curve, including its abrupt change of slope at the first cracking load, but also the dynamic dislocation in the load-stress diagram at the first cracking load after decompression in bonded prestressed beam. Beyond that dislocation point, the beam can o longer be considered to behave elastically, and the rise in the compressive C-line stabilize and stop so that the section starts to behave like a reinforced concrete section with constant moment resistance arm [14]. If the beam is unbonded, the stress in steel will be different from the bonded beam.

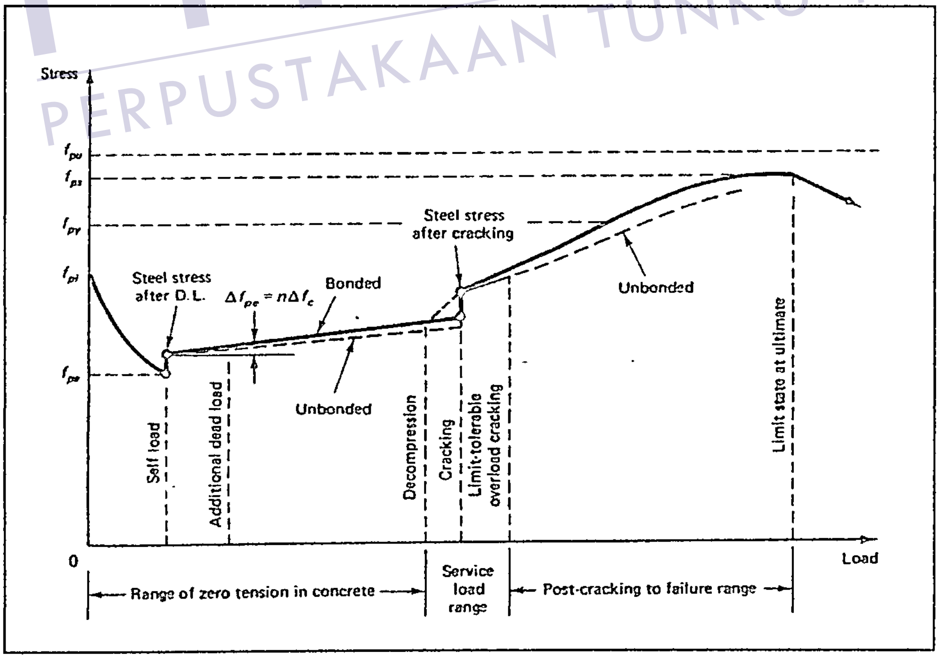


Figure 2.5: Stress-load curve of typical prestressed beam (T. Y. Lin, 1982)

2.4.3 Stresses in concrete due to loads

Section resisting external moment for a pretensioned beam is the combined section where steel is always bonded to the concrete before external moment is applied. This stresses are computed by usual elastic theory whether due to the beam's own weight or to any externally applied loads. When the beam is post-tensioned and bonded, any load applied after the bonding taken place, the transformed section should be used as for pretensioned beams. If the load is applied before bonding takes place. It acts on the net concrete section. Hence, only used the basis stress estimated. For post-tensioned unbonded beams, the net concrete section is the proper one for all stress computations. Take note that, when the beams is unbonded, any bending of the beam may change the overall prestress in the tendon, the effect of which can be separately computed.

2.4.4 Stresses in concrete due to prestress

Referring to Figure 2.6, for pretensioned member, when the prestress in the steel is transferred from the bulkheads to the concrete, the force that was resisted by the bulkheads is now transferred to the both steel and the concrete member. The release of the resistance from the bulkheads is equivalent to the application of an opposite force *Fi* to the member.

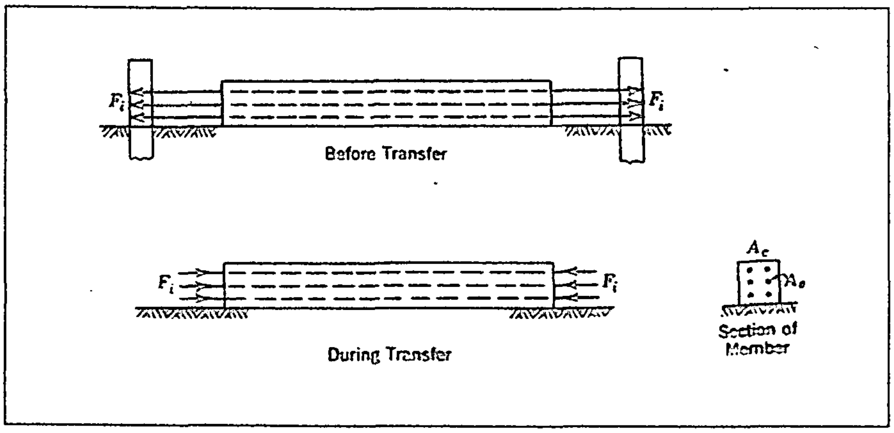


Figure 2.6: Transfer of concentric prestress in a pretensioned member (T. Y. Lin, 1982)

In usual practice, the immediate reduction of the prestress in the steel, being reduced by a loss resulting from elastic shortening of concrete. After the transfer of prestress, further losses will occur owing to the creep and shrinkage in concrete, and in practice being simply to allow for the losses by an approximate percentage. In other words, the simple formula $f = F/A$ is always used, with the value of F estimated for the given condition, and the gross area of concrete used for A. For post-tensioned member, the same reasoning holds true. Suppose that there are several tendons in the member prestressed in succession. Every tendon that is tensioned becomes part of the section after it is bonded by grouting. The effect of tensioning any subsequent tendon on the stresses in the previously tensioned ones should be calculated on the basis of the transformed section. The usual procedure is simply to use the formula $f = F/A$ with F based on the initial prestress in the steel.

2.5 Flexural types of failures

The typical load-deflection response of a prestressed concrete beams as describe in Figure 2.4 is a desirable type of behaviour; design limitation in various codes tend in general to ensure such behaviour. Other types of behaviour can however, be observed (see Figure 2.7). As the load is progressively increased on a simply supported prestressed concrete beam, the following types of failures might occur depending on the amount of steel reinforcement provided [Naaman, 1982].

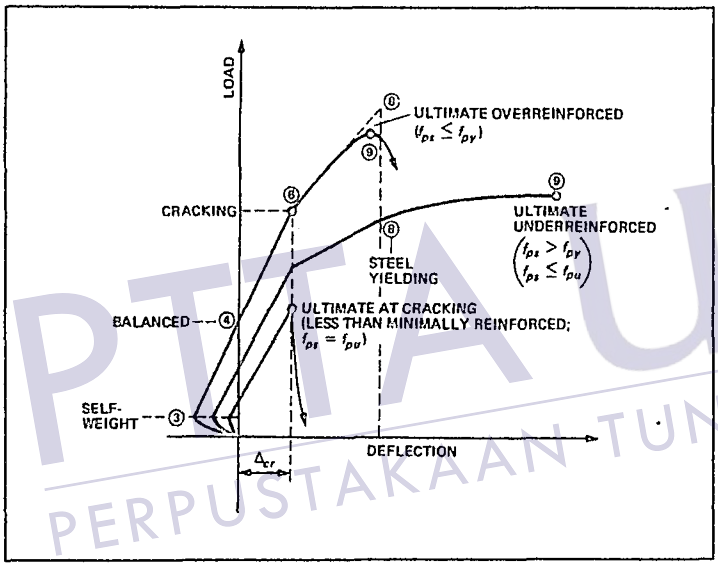


Figure 2.7: Typical change in load-deflection curve with an increase in the amount of reinforcement (Naaman, 1982)

i. Fracture of the steel immediately after concrete cracking and thus sudden failure.

ii. Crushing of the concrete compressive zone, preceded by yielding and plastic extension of the steel.

iii. Crushing of the concrete compressive zone before yielding of the steel.

2.6 Analysis of section at ultimate

The purpose of the analysis at ultimate load is generally to determine the nominal moment resistance (moment at ultimate behaviour) of the section assuming that the cross-sectional dimensions and materials properties are given. Take note that the stress in the steel and in the concrete at ultimate is outside their linear range of behaviour. Codes of practice tend to propose some assumption and widely accepted assumption such as [Naaman, 1982]:

i. Plane sections remain plane under loading where linear strain distribution exists along the concrete section up to ultimate.
ii. Perfect bond exists between steel and concrete but the case of unbonded tendons must be treated separately. Any strain change in the steel due ti applied load is equal to the strain change in the concrete at the level of the steel at the same load.

Following is the additional assumptions propose by ACI code:

iii. The limiting compressive strain of the concrete ε_{cu} is equal to 0.003, regardless of the strength of the concrete, shape of the section and amount of the reinforcement.
iv. Tensile strength of the concrete is neglected. Thus the point of zero stress represents the boundary between cracked and the uncracked part of section.

v. Total force in the concrete compressive zone can be well approximated by considering a uniform stress of magnitude 0.85f'c over a rectangular block of width *b* and depth $a=\beta_1 c$.

2.6.2 Flexural strength by strain –compatibility analysis

Here, discussion is based on Arthur H. Nilson writing in *Design of Prestressed Concrete* in 1987. For rectangular section and referring to Figure 2.8, the strain distribution (1) results from application of effective prestress force P_e, acting alone after all losses, is shows in Figure 2.8a. At this stage, the stress in the steel and the associated strain are respectively,

$f_{pe} = P_e/A_p$ .... (2.1)

$\varepsilon_1 = \varepsilon_{pe} = f_{pe}/E_p$ .... (2.2)

Next, line (2) shows an intermediate load stage corresponding to decompression of the concrete at the level of steel centroid. Assuming that bond remains intact between the concrete and steel, the increase in steel strain produce as loads pass from stage (1) to stage (2) is the same as the decrease concrete strain at the level in the beam and it is given by expression

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