EFFECT OF HIGH STRENGTH CONCRETE ON CAPACITY OF PRESTRESSED BEAM FOR BRIDGE CONSTRUCTION

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By

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I hereby declare that all corrections and comments made by the supervisor(s)and examiner have been taken into consideration and rectified accordingly.

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(Signature of Examiner)

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Date :

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ABSTRAK

Konkrit pra-tegasan telah menjadi kaedah pembinaan yang penting dan lazim digunakan dalam kejuruteraan jambatan. Rasuk jambatan pra-tegasan pra-tuang mempunyai kelebihan dalam mengawal retakan dan pemesongan berbanding dengan konkrit bertetulang konvensional, dengan itu rasuk jambatan yang lebih panjang boleh dicapai. Dalam industri konkrit pra-tuang, standard rasuk jambatan pra-tegasan pra-tuang standard kini dihasil menggunakan konkrit kekuatan biasa sehingga 50 MPa. Dengan kemajuan dalam teknologi konkrit, applikasi konkrit kekuatan tinggi dalam konkrit pra-tegasan mungkin dapat memberi kelebihan kepada industri. Oleh itu adalah penting untuk mengetahui peratusan penambahan dalam kapasiti seksyen rasuk apabila rasuk jambatan pra-tegasan direka bentuk dengan konkrit kekuatan tinggi. Kesan konkrit kekuatan tinggi pada peratusan pengurangan dawai pra-tegasan juga dikaji. Sebanyak 15 standard rasuk jambatan pra-tegasan standard model yang terdiri daripada rasuk-I, rasuk-Y, rasuk-M, rasuk-U, rasuk-T terbalik dan rasuk-PRT dengan pelbagai kedalaman dan rentang telah dikaji. Reka bentuk dan analisis dilakukan menurut standard BS 5400. Tegasan dalam konkrit dan pemesongan diperiksa agar mematuhi had kebolehkhidmatan. Didapati bahawa konkrit kekuatan tinggi boleh meningkatkan kapasiti momen rasuk pra-tegasan. Namun begitu, standard rasuk jambatan sekarang didapati tidak sesuai dilaksanakan dengan konkrit kekuatan tinggi kerana rasuk direka bentuk untuk kekuatan konkrit sehingga 50 MPa sahaja. Penambahbaikan dalam kapasiti momen dihadkan oleh tegasan dalam dawai pra-tegasan. Untuk kapasiti ricih, didapati peratusan peningkatannya agak rendah dan boleh diabaikan. Keputusan yang sama ditunjukkan pada pengurangan keluasan dawai pra-tegasan yang diperlukan. Seksyen rasuk dan pra-tegasan perlu direka bentuk semula agar dapat menggunakan sepenuhnya kebaikan konkrit kekuatan tinggi.

ABSTRACT

Prestressed concrete has become an important and commonly used construction method in bridge engineering. Precast prestressed bridge beam has advantage of better cracking and deflection control compared with conventional reinforced concrete, therefore longer span bridge beam can be achieved. The current standard precast prestressed bridge beam produced in precast concrete industry uses normal strength concrete up to 50 MPa. With the advancement of concrete technology, application of high strength concrete in prestressed concrete might able to bring advantage to the industry. This study was carried out to investigate the percentage increase in beam section capacity when prestressed bridge beam is designed with high strength concrete. The effect of high strength concrete on the prestress strands reduction is also examined. A total of 15 standard prestressed bridge beam models consisting of I-beams, Y-beams, M-beams, U-beams, inverted T-beams and PRT-beams with various depth and span have been studied. Design and analysis were carried out according to BS 5400 standard. The stresses in concrete and deflections were checked to comply with the serviceability limit. It is found that high strength concrete is able to increase the moment capacity of prestressed beam. The percentage increase is dependent on the sectional shape and prestress design. However, current standard bridge beam is found unsuitable to be used together with high strength concrete as the current beams are designed for concrete strength up to 50 MPa. The improvement in beam capacity is limited by the stresses in prestress strands. For shear capacity, it was found that the percentage increment is low and negligible. The result showed the same case for the reduction in strand area required where the percentage of reduction in strand area required is limited by the stresses in prestress strands. The beam section and layout of prestressing strands need to be redesigned in order to make full use of the benefit of high strength concrete.

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CHAPTER 1

INTRODUCTION

1.1 Background of Precast Prestressed Concrete Bridge Structures

Precast concrete is defined as concrete that is cast elsewhere from its final position and used in structural or non-structural applications (ACI 116R-00, 2000). Precast concrete now is the most recent major form of construction introduced in the structural engineering. It has become a well established method of construction where its technology is available in most developed and developing countries. In fact, Malaysia has started to transform its conventional method of construction to prefabrication using industrialized building systems (IBS), where the most common IBS component used in Malaysia is precast concrete. Precast concrete technology has more advantages over conventional construction methods, for example improved buildability, enhanced productivity and faster construction. Therefore, precast concrete has been widely used in constructions such as drain, pile, building structural framing system, retaining wall and bridge.

Bridge is categorized into seven main types: beam, truss, arch, tied arch, cantilever, suspension and cable stayed bridge, as shown in Figure 1.1. Precast concrete is utilized mainly in the beam bridge construction. The use of simply supported precast beams provides an economical form of construction, particularly where there is restricted access beneath the bridge for construction. However, bridge construction requires long span beam to support the massive traffic loading. Normal reinforced precast bridge beam has disadvantage of limited span length, due to cracking and deflection problem. Therefore, precast prestressed concrete bridge beam is introduced in the industry.

(a) Beam bridge: Confederation Bridge, Canada

(b) Truss bridge: Arun Khola Bridge, Nepal

(c) Arch bridge: Mostar Old Bridge, Bosnia and Herzegovina

(d) Tied-arch bridge: Shinhamadera Bridge, Japan

(e) Cantilever bridge: Minato Bridge, Japan

(f) Suspension bridge: Pearl Bridge, Japan

(g) Cable-stayed bridge: Sri Wawasan Bridge, Malaysia

Figure 1.1: Example of different type of bridges (source: CNN, 2012)

In the year of 1938, the first prestressed concrete bridge was built near Oelde, Germany (Sigrist and Bäurich, 2006). The concept was to superimpose a predetermined state of stress to those stresses in a structure arising from the loads. Steel reinforcement bars are substituted with high tensile cables, tensioned by jacks and locked to the concrete. Thus they compressed the concrete, ridding it of its cracks, improving both its appearance and its resistance to deterioration.

Prestressing of concrete is now a well-established techniques in all countries, with a wide portfolio of bridge types and span lengths constructed. For pretensioned bridge decks, the common types of beams include I-beams, M-beams, inverted T-beams, U-beams, PRT-beams and Y-beams as shown in Figure 1.2. Various types of beams have different span limits. Figure 1.3 shows some examples of existing prestressed concrete bridges.

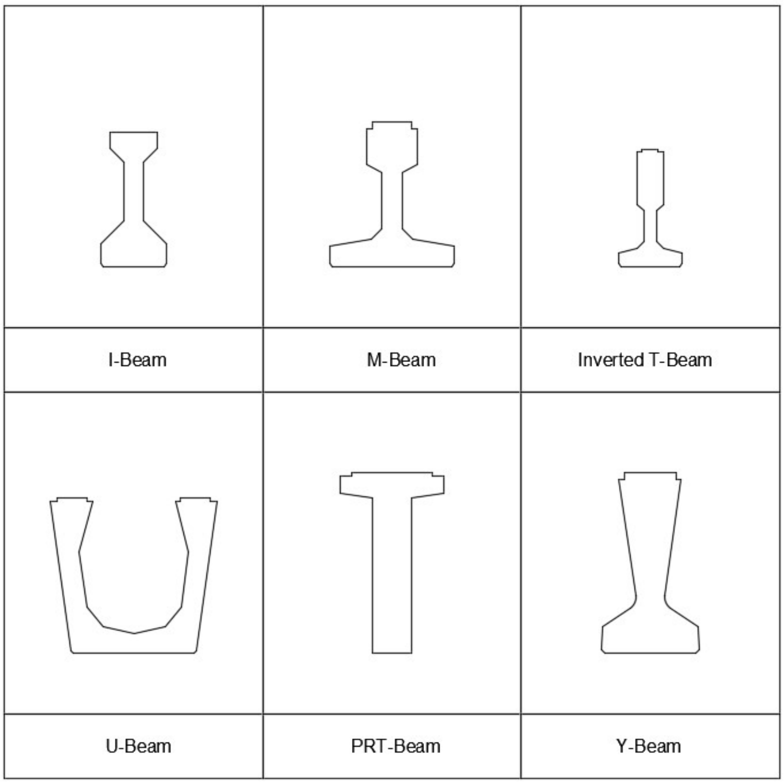

Figure 1.2: Different cross-sectional shape for precast prestressed bridge beams

(a) Plougastel Bridge, France
(Structurae, n.d.)

(b) Sungai Kelantan Bridge, Malaysia
(Giga Engineering & Construction, 2001)

(c) Brücke Hesseler Weg Bridge, Germany (The first prestressed concrete bridge)
(Sigrist and Bäurich, 2006)

Figure 1.3: Example of prestressed concrete bridges

The principle of prestressing is explained in Figure 1.4. Prestressing forces that is applied to concrete section counteracts the stresses due to external loadings. The resultant stress is thus reduced, especially the tension stress at the bottom of the concrete section. Prestressed concrete structures therefore have the advantage of higher load bearing capacity without cracking, as shown in Figure 1.5.

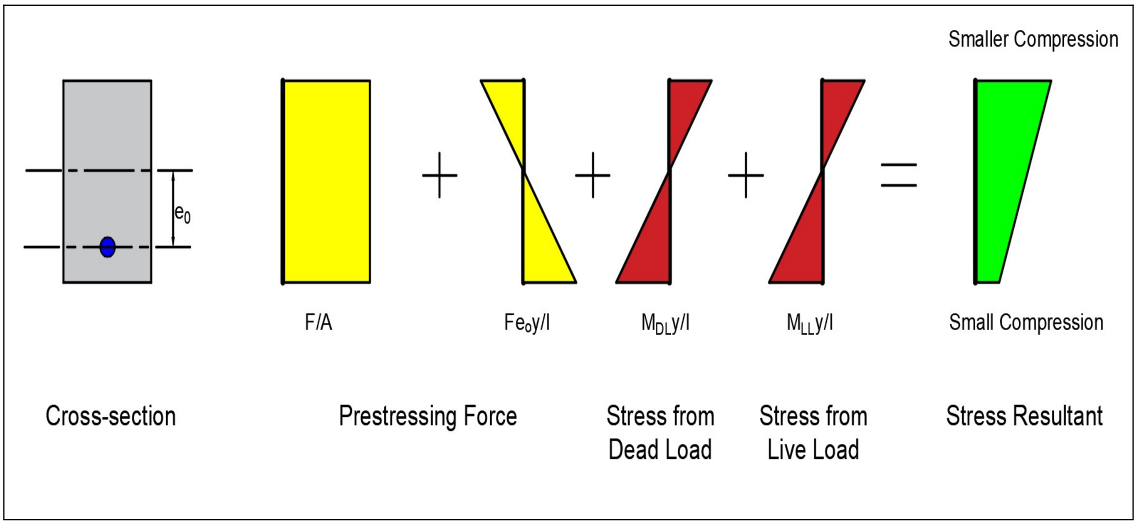

Figure 1.4: Stress block showing principle of prestressing

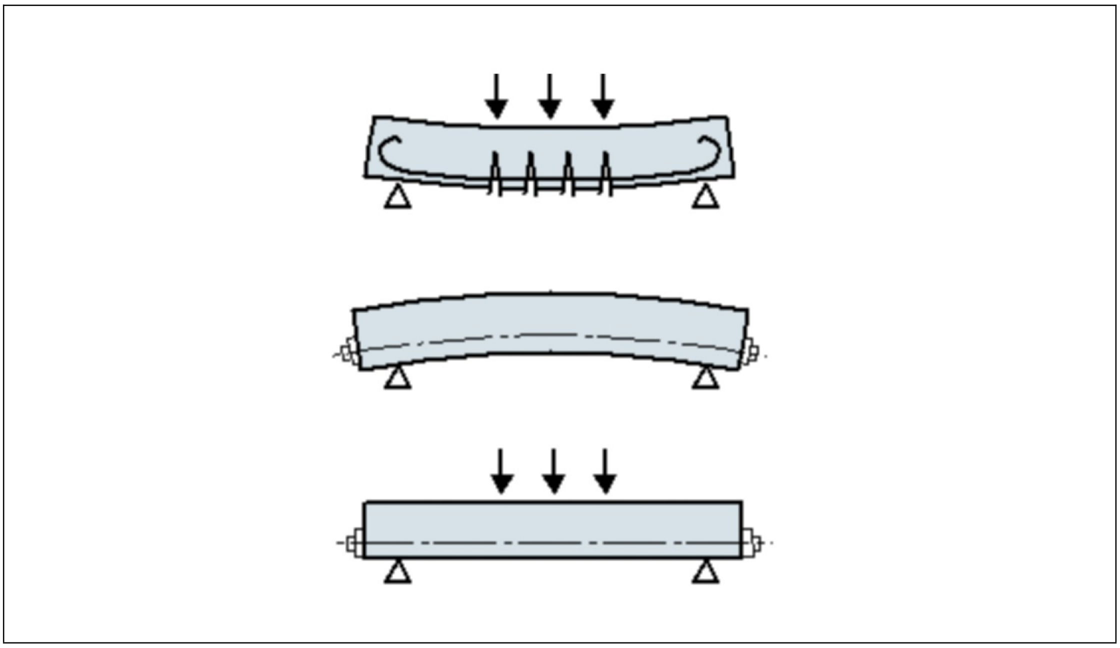

Figure 1.5: Higher load bearing capacity without cracking of prestressed beam (source: sanfield limited, n.d.)

As a result, section of beam structure can be more efficiently utilized. Such more efficient usage of material of section will lead to relative lighter section in comparison with normal reinforced concrete bridge structures without prestressing.

1.2 Background of High Strength Concrete

High strength is defined as concrete having a 28-day cylinder compressive strength of at least 6000 psi, which equals to 41 MPa (ACI 363R-92, 1992). ACI recognizes that the definition of high-strength varies on a geographical basis. Different definition of high strength concrete exists, and changing with time basis. Portland Cement Association has defined a strength classification system which is a helpful tool for describing high-strength concrete. The classification is shown in Table 1.1. Concrete strength of 50 MPa or less is considered as normal strength concrete; while concrete strength of more than 50 MPa is considered as high strength concrete. This definition is used in this research.

Table 1.1: Strength classification of concrete (Concrete Technology Today, 1994)

	Conventional concrete	High-strength concrete	Very-high-strength concrete	Ultra-high-strength concrete
Strength, MPa	< 50	50-100	100-250	> 150
Water-cement ratio	> 0.45	0.45-0.30	0.30-0.25	< 0.25

1.3 Problem Statement

Section capacity of prestressed beam is affected by factors such as the beam cross-sectional shape, layout of strands and material used. As such, use of high strength concrete could lead to more efficient prestressed beam, in terms of load carrying capacity to self-weight ratio. Nowadays the concrete technology is well developed in terms of producing concrete with higher strength more than 50 MPa. However, the capacity and performance of prestressed components are not fully utilized considering the current development of concrete technology. Precast manufacturers still use concrete with strength of about 50 MPa for the prestressed concrete components, which is in the normal strength concrete category.

Therefore this study is aimed at determining the effect of using high strength concrete on the section capacity of prestressed beam for bridge construction.

1.4 Objectives

This study is carried out with the following objectives:

(i) To investigate the effect of high strength concrete on the section capacity of prestressed precast beam.

(ii) To investigate the reduction in strand required in prestressed precast beam using high strength concrete.

1.5 Layout of Thesis

Chapter One describes the background, problem statement and the main objectives of this research.

The past studies about prestressed concrete that have been done are described in Chapter Two. It is mainly divided into studies on prestress losses, structural behavior, analysis, feasibility and performance of prestressed concrete.

Chapter Three is the summary of procedure, including the selected precast prestressed concrete bridge beam models, justification of bridge loading, design and analysis of prestressed concrete beams models.

Chapter Four presents the result and discussion of effect of high strength concrete on the section capacity and also the strand reduction of the prestressed concrete beam model.

Chapter Five presents the conclusion of the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Research works that have been carried out on prestressed concrete beams in the past can be grouped into:

(i) Losses in prestressed concrete

(ii) Structural behaviors of prestressed beams with different material

(iii) Analysis of prestressed concrete bridges

(iv) Feasibility and performance studies

Review of the research studies are presented in the following sections.

2.2 Losses in Prestressed Concrete

Barr et al. (2008) compared the prestressed losses for a prestressed concrete bridge made with high-performance concrete. The total measured prestress loss was as large as 28% of the total jacking stress. Due to the higher stresses, this loss is larger than would be expected for a girder made with conventional strength concrete.

Myers and Bloch (2013) monitored the time-dependent losses of prestressed high strength concrete and high strength self-consolidating concrete pedestrian bridges. Two precast prestressed high strength concrete and high strength self-consolidating concrete specimens were designed and erected for site investigation. Studies conducted found that high strength self-consolidating concrete has a higher loss percentage than high strength concrete, of about 21% for elastic shortening losses and 10% for total losses. The additional prestress loss showed greater effect that creep had on high strength self-consolidating concrete than high strength concrete.

2.3 Structural Behaviors of Prestressed Beams with Different Material

Cuenca and Serna (2013) evaluated the shear behavior of prestressed precast beams made of self-compacting fiber reinforced concrete. Under different conditions such as combination of fibers with stirrups, the possible influence of flange width on shear strength and the interaction of fibers with other important parameters such as flange width and longitudinal reinforcement, the shear evaluation of nine prestressed I-beams of different flange dimensions were analyzed experimentally. The result showed that fibers act as additional reinforcement to stirrups.

Vázquez-Herrero et al. (2013) compared the flexural behavior of lightweight and normal weight prestressed concrete beams. Two types of lightweight concrete and a conventional normal weight concrete with the same compressive strengths were used for structural performance comparison of the beams. The results of the production and monitoring of scaled prestressed concrete beams at a precast yard and the subsequent flexural testing were compared. It was concluded that lightweight concrete is not suitable for prestressed concrete bridge beams, due to the potential reduction in durability and bearing capacity. The reduction in durability and bearing capacity are caused by the splitting cracks in prestressed lightweight concrete beams.

2.4 Analysis of Prestressed Concrete Bridges

Norachan et al. (2014) carried out the three-dimensional analysis of segmentally constructed prestressed concrete bridges using hexahedral elements with realistic tendon profiles. Geometric non-linearity, time-dependent effects, variations of the structural configuration and load histories during the construction process were taken into account. In order to include realistic tendon profiles, the prestressing tendon has been developed based on a system of piecewise linear prestressing segments. To demonstrate the validity and efficiency of the analysis, numerical examples of prestressed concrete structures have been carried out and the results showed similarity with the previous studies. The structural responses during construction and at long-term period were predicted. Time-dependent effects due to creep, shrinkage and relaxation showed a significant impact on the long-term response of the bridge. Based on the numerical results, it is found that complex responses from the three-dimensional analysis of segmentally constructed prestressed concrete bridges can be realistic captured by the proposed procedure.

Marti et al. (2016) presented an automated procedure for optimizing the design of prestressed concrete U-beam road bridges based on embodied energy. Heuristic optimization was used to search for the best geometry, concrete type, prestress steel and reinforcement for slab and beam. The relationship between span length and embodied energy was described by a good parabolic fit for both optimization criteria. The findings indicated that the objectives do not exhibit conflicting behavior and also optimum energy designs are close to the optimum cost designs. Reduction in reinforcement in the slab as well as increase in volume of concrete in both slab and beam is recommended, in order to achieve higher energy efficiency. The web inclination angle is also recommended to be increased with depth for longer span lengths to maintain the optimum slab span lengths in the transverse direction.

An analytical method employing the strain-based shear strength model was developed by Park et al. (2012) to predict the shear strength of prestressed concrete beams. Assumption that the compression zone of intact concrete in the cross section primarily resisting the applied shear force was made. The proposed model was applied to existing test specimens and the results were found to be reasonable precised. The results showed that it can be used for both normal reinforced and prestressed concrete beams.

2.5 Feasibility and Performance Studies

Tong et al. (2016) investigated the intertwined effects of concrete viscoelasticity, cracking and plastic softening on the time-dependent deformation by a case study of a large-span prestressed concrete bridge carrying heavy traffic flow. The unified model was implemented in ABAQUS and a large-span prestressed concrete bridge was analyzed using 3D-type formulation. Compared with the inspection reports, the deflection history at mid span, deformed profile of the whole bridge and distribution of concrete cracking were adequately captured in the simulations. The cyclic load-induced damage accumulation process played a non-negligible role and traffic management plans were needed for heavy trucks to mitigate the risk of excessive deflection and concrete degradation.

Schnittker et al. (2009) studied the effects of increasing the allowable compressive stress at prestress transfer. The current code provision regarding the allowable maximum compressive stress at prestress transfer in ACI 318-08 is as follows:

Stresses in concrete immediately after prestress transfer (before time-dependent prestress losses): (a) Extreme fiber stress in compression except as permitted in (b) shall not exceed $0.60f'_{ci}$. *(b) Extreme fiber stress in compression at ends of simply supported members shall not exceed* $0.70f'_{ci}$.

The study recommended that the extreme fiber stress in compression except at the ends of simply supported members to be increased to $0.65f'_{ci}$ from the existing $0.6f'_{ci}$ as specified in ACI 318-08.