# RELIABILITYY ANALYSIS OF PRESTRESSED CONCRETE BRIDGE GIRDER BEAM

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**To Chechi the one and only.**

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# ABSTRACT

Recent studies undertaken in the United States and Europe have shown that there are many highway bridges rated as structurally deficient requiring rehabilitation or replacement due to the increase traffic flow and modern truck loads. The objective of this dissertation is to compare the reliability based load factor for prestressed bridge girders against the deterministic load factor given in six (6) codes namely; BS5400 Pt.2, AASHTO, Canadian Code (OHBDC), Eurocode, Australian Code (Austroads) and JKR specifications. 'Y5' prestressed bridge girder with a resistance of 4192kNm assumed to be a constant are considered. The load parameters and the bridge spans are treated as random variables. The statistical parameters are based on available literature and test data. The reliability indices for load factor are calculated by iteration utilizing Monte Carlo simulation. Based upon the results obtained it can be concluded with confidence that in the design of primary highway loads, the load factor given in the codes can be reduced by approximately 10 to 13%. The results also indicate that AASHTO is the most conservative code while BS5400 Pt.2 and Eurocode are the most permissive. This would mean that using BS5400 Pt.2 or Eurocode will result in a cost effective bridge girder beam.

# ABSTRAK

Objektif dissertasi ini adalah untuk memperbandingkan prinsip keboleharapan rasuk jambatan prategangan berdasarkan kepada faktor beban hidup keboleharapan dengan faktor beban hidup konvensional (deterministik) yang diberikan dalam enam (6) piawai-piawai rekabentuk iaitu; BS5400 Pt.2, AASHTO, Piawaian Kanada (OHBDC), Eurocode, Piawaian Australia (Austroads) dan spesifikasi JKR. Rasuk jambatan prategasan 'Y5' dengan nilai keupayaan masimum 4192kNm adalah dianggap tetap ataupun sebagai satu konstan. Parameter beban dan panjang rasuk jambatan adalah dianggap sebagai pembolehubah rawak. Parameter statistik beban dengan panjang rasuk jambatan adalah berdasarkan kepada kajian literatur sediada serta kajian makmal. Prinsip keboleharapan rasuk jambatan berdasarkan kepada faktor beban hidup adalah dijalankan dengan kaedah simulasi Monte Carlo secara berulang. Melalui kajian keboleharapan dengan simulasi Monte Carlo, keputusan yang didapati menunjukan bahawa faktor beban hidup yang diberikan dalam piawaian rekabentuk boleh dikurangkan sebanyak 10% hingga 13%. Keputusan kajian ini mendapati bahawa piawan ASSHTO merupakan satu piawan yang paling konservatif manakala piawaian BS5400 Pt.2 dan Eurocode adalah piawaian-piawaian yang paling permisif. Ini bermakna dengan menggunakan piawaian BS5400 Pt.2 atau Eurocode akan memberikan satu rekabentuk rasuk jambatan yang kos effektif.

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## NOMENCLATURES

| | | |
|---|---|---|
| $(S)$ | - | loads |
| $(R)$ | - | resistance |
| $P_f$ | - | probability of failure |
| $f$ | - | resistance factor |
| $g_i$ | - | load factor |
| $R_n$ | - | nominal design resistance |
| $S_n$ | - | nominal load effects |
| $G\ (\ )$ | - | limit state function |
| $x_i$ | - | random variable |
| $\mu_x$ | - | mean value |
| $n$ | - | number of observation |
| $Var\ (x)$ | - | variance |
| $\sigma_x$ | - | standard deviation |
| $COV$ | - | coefficient of variation |
| $\infty$ | - | infinity |
| $m_x$ | - | random variable of moment |
| $b$ | - | reliability index |
| $\Phi^{-1}$ | - | inverse standard normal distribution function |
| $\partial$ | - | partial differential |
| $f_{cu}$ | - | concrete strength |
| $f_y$ | - | steel strength |
| $\lambda$ | - | bias factor |
| $\gamma_{f3}$ | - | live load factor |
| $M_{av}$ | - | average moment |

| | | |
|---|---|---|
| $l$ | - | length |
| $b$ | - | breath/width |
| d | - | effective depth |
| $f_{cn}$ | - | complementary function |
| ULS | - | ultimate limit state |
| SLS | - | serviceability limit state |
| $f\,(\,)$ | - | probability density function |
| $\sum$ | - | summation equation |
| E (x) | - | expected value of X |
| PDF | - | probability density function |
| CDF | - | cumulative density function |
| (N) | - | number of iterations |
| w | - | loads |
| KEL | - | knife edge load |
| M | - | moment |
| M (x) | - | mid span moment distribution |
| % | - | percentage |
| e | - | exponent |
| Z | - | safety margin |
| $m_R$ | - | mean of resistance |
| $m_S$ | - | mean of loads |
| ln | - | lognormal |
| UDL | - | uniformly distributed loads |

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# CHAPTER 1

# INTRODUCTION

## 1.1 General Introduction

Highway bridges and associated structures in some ways influence the visual quality of our surroundings with their sophisticated appearance and they are in fact highly functional artifacts with long service life which, is regularly used and seen by the masses. Highway bridges are critical link and form a considerable investment in infrastructure that should be kept safe and serviceable. The design aspects of highway bridges on the other hand are influenced by the application of loads and these form the fundamental data in designing the bridge. The basic philosophy of the application of loads is that the worst case scenario of the loads is taken as the basis of the bridge design.

The last ten (10) years has seen the rapid development of reliability based assessment methods to help engineers tackle the analysis, quantification, monitoring and assessment of structural risks, undertake sensitivity analysis of inherent uncertainties and make the appropriate decisions about the performance of a structure.

The structure maybe at the design stage, under construction or in actual use. Highway bridge damage or failure especially those involving the loss of life, are very rare and usually have causes outside the realm of typical design specifications. The primary emphasis in bride design is the application on live loading effects and in this instance the reliability with respects to live loadings due to HA and HB loads (Frangopol, 1999). Highway bridges assessed with the reliability methods have been found to be structurally deficient and required replacement to allow them to carry modern truck traffic and the increase in annual traffic (*Ibid*). The cost to the relevant infrastructure agencies to rehabilitate these bridges is enormous. In short, reliability methods used in highway bridge design can be an effective method in producing a high degree of performance structure which is cost effective. This forms the quintessential requirement of awareness in using the reliability methodology to highway bridge design.

## 1.2 Background of The Problem

Recent studies undertaken in the United States and Europe have shown that there are many highway bridges rated as structurally deficient requiring rehabilitation or replacement to allow them to carry increased traffic flow and modern trucks loads (Nowak, 2000). The deficiency of these highway bridges are primarily from the live loading effect and not from the threats like corrosion, collision, wind and scouring. There is now an underlying realization that the analytical techniques developed for the bridge design are in many cases unable to accurately model the structural behavior of highway bridges.

This has resulted in underestimating the actual load capacity of bridge girders in the design assessments. In the design of highway bridges the designer must have an understanding of the types and magnitude of the loads that are expected to act on the bridge during its lifetime. It has been expounded earlier that the basis of bridge design relies on the worst case loading scenario or in other words, load combinations giving the worst bending moments and stresses. The HA and HB loads used in combinations are derived from the British Standard 5400 (Part 2) or from local specification such as JKR which uses LTAL and SV loadings in lieu of HA and HB loads although both uses the same methodology to derive the ultimate and serviceability limits. There are five (5) load combinations and combinations one (1) to three (3) are called the principle combinations while combinations four (4) and five (5) are called the secondary combination. These formed the basic data to assess the bridge comparing it to the ultimate or the serviceability limit state. This method of analysis can be described as deterministic, resulting in bridges that are an underestimation of the actual load carrying capacity. The fact that the loading combinations are random variables and thus absolute safety or zero probability of failure cannot be achieved. Vehicle comes in various shapes and sizes, traffic passing over a bridge fluctuates with time and at any given time it is impossible to quantify the number of vehicles and its specifications passing over a bridge. This makes the load a random variable.

The loading on a highway bridge is further compounded by the issue of heavy vehicles being modified to carry heavier loads either legally or illegally (lorry hantu, overloading of lorries etc.).

The HB or SV loads are thus constantly changing compared to what is given in the codes and specifications. This uncertainty in the context of codes and specification is taken care by the “safety factor” however; the accuracy of using this safety factor is subjective and cannot be taken as the absolute although engineers design with the later in mind.

In many cases, the bridges will exhibit no outward signs of distress. Although this does not, in itself, imply that failure may not be imminent; it is likely that some form of damage or significant deformation will precede collapse in cases of ductile failures of concrete bridge girders. This brings into question the appropriateness of using elastic analysis for the determination of ultimate strength for many types of bridges; and in particular short span concrete bridge girders which have been found to be deficient in flexure (Thoft-Christensen, 1999).

Clearly there is a need to review and refine the existing methods and to develop improved techniques which can more realistically model the ultimate load capacity of bridges. Current codes of practice are written with the implicit assumption that the design and assessment of bridges will usually be undertaken using linear elastic analysis techniques. Elastic theory is well established and is supported by many computer software packages, and has been found most satisfactory for the design of bridges. As a lower bound method the engineer can be confident that the analysis method should be conservative and hence safe.

The questions that are glaringly unanswered are what does "failure" actually mean in an elastic analysis and what are the consequences of such failure in terms of both risks to life and economic terms? The conventional approach to the assessment of concrete bridge deck is to initially perform a simple elastic beam analysis using a representative strip of the bridge girder.

If this "quick" check shows that the structure to be inadequate, a more detailed linear elastic analysis allowing for transverse distribution of loads would probably be performed using either a grillage or finite-element analysis. These results are then examined to identify individual locations at which the maximum calculated moments or shears exceed the estimated ultimate capacity of the section. The decision to strengthen or replace a structure is commonly made on the basis of these results. Transverse steel bars, shear bars are added to the bridge girder to supplement this deficiency.

In reality concrete structures will crack under heavy loads resulting in a change in stiffness of the bridge girder. Even when the ultimate moment capacity of a section of the bridge girder is exceeded, loads will be redistributed elsewhere in the deck slab provided that the deck possesses sufficient ductility and it does not fail prematurely in shear. As a result, linear elastic analysis will not accurately model the distribution of stresses or the actual behavior in the post-elastic range where non-linear effects dominate. Elastic methods can be very conservative since failure of one element in the structure is typically used to define failure of the structure as a whole. In the cases of flexural failure, the consequences are likely to be small and only may affect the serviceability of the structure.

If one accepts the that serviceability criteria does not govern and collapse is a criterion on which to base the assessment, such conservativeness is not warranted for concrete bridge girder for which ductile flexural failure is the critical mechanism of failure. Once an individual section has reached ultimate or yield capacity, the failure must develop into full collapse mechanism before the structure will actually fall down (Melchers, 1987). Elastic models are still relied upon as the primary analyses tool for assessing concrete bridge girder and full scale loads tests conducted shows that concrete bridges are often able to carry loads well in excess of the "theoretical" capacity calculated using this technique (*Ibid*).

It is thus important to investigate the options available to an engineer if some form of alternative assessment can be carried out in tandem with his elastic models. Reliability modeling and assessment is an appropriate solution to the problem of quantifying the variables (loading in this case) and providing an accurate range of limit states based on primary highway loadings. The probability of failure of bridge decks can be predicted with high accuracy using the reliability based assessment.

The research problems can be summarized as follows;

i) The primary highway loadings (HA loads) given in the relevant codes are random variables and thus cannot be quantified in a deterministic manner. What is the best approach in modeling this variable?

ii) How do we evaluate the load models that has been developed in (i) above?

iii) How do we measure the probability of failure of the bridge girder arising from primary highway loadings (HA loads)?

iv) Are there any difference between the various codified approach to bridge girder analysis (ULS and SLS methods) and the reliability based approach to analyze a bridge girder? If there are, what are the major differences?

v) How the implementation of reliability based modeling and evaluation of bridge girder based on primary highway loading can enhance the overall safety level of a bridge girder?

vi) Are there any imminent cost saving arising from using reliability based assessment in bridge girder analysis?

## 1.3 Objectives of Study

The objectives of this study are to;

i) Conduct an investigation approach to formulate the various load factor models from various codes which can be used to analyze maximum mid span moment effects on a standard prestressed bridge girder beam.

ii) Assess the reliability of the standard bridge girder based upon the load models and load factors given by various codes and specifications namely JKR, BS 5400 Part 2, AASHTO, Eurocode, Austroads (Australian Highway Code) and Canadian Code (OHBDC).

## 1.4 Scope of Study

The scope of study covered literature review from various sources and codes of practice namely BS 5400 Part 2, JKR specifications, AASHTO, Eurocode, Austroads (Australian Highway Code) and Canadian Codes specification on primary loadings (HA loads) and their respective load factors. This study carried out a statistical approach to model primary loadings (HA loadings) to highway bridge girders and evaluate the result with the conventional elastic analysis approach to bridge girder designs. The data for the conventional and reliability based method of analysis are based on an arbitrary data as follows;

1) Bridge Span = 42 meters.
2) Carriageway Width = 12 meters
3) Footway width at both shoulders = 2 meters.
4) Bridge Girder = Standard Prestressed Girder Beam.

Computer software namely MATLAB Ver. 6.5.1 was utilized to run statistical process (probabilities) approach to model the maximum moments at mid span arising from primary highway loadings (HA & KEL loads). The results from utilizing various load factors from the codes will then be compared to the conventional elastic model analysis of the bridge girder. This would result in some difference which then can be used to evaluate which codes gives rise to a conservative design and which codes give rise to a permissible design.

The reliability based assessment of bridge girder data would be crossed referenced with the most permissive code to check if there are can be any significant reduction in member size and subsequent cost savings.

Finally the scope of study demonstrated that by using the reliability based assessment of highway bridge decks, can supplement if not enhance the final analysis for any bridge girder.

### 1.5 Importance of Study

This study basically showed on how to model primary highway loads (HA loadings) to bridge girder using reliability approach (probability approach) and how to evaluate the models based on the load factors given in various codes mentioned above. The data from reliability analysis could perhaps be used to develop reliability based design codes or it can be used to supplement the load factors used in the various codes.

The result data from the reliability analysis can be used by design engineers to enhance their decision making in analyzing highway bridge girders. This would in some parameters benefit engineers to improve their accuracy and reduce some uncertainties in the design of highway bridges. Lastly on the whole the design would be envisaged to be safe for its lifetime and cost effective.

## 1.6 Limitations of Study

The limitation of this study is that other loads such as transient highway loadings such as wind loads, collision loads, dynamic effects, scouring, braking and centrifugal loads, shrinkage and thermal effects are not considered in this study. This is primarily due to the fact that modeling these loads would be too large an endeavor to undertake. Therefore only primary highway loading namely HA, KEL and Footway Loading are taken into account to demonstrate highway bridge load modeling.

## 1.7 Thesis Organization

This thesis is organized into six (6) chapters. Chapter one (1) will consist of the problem background, research objectives, scope and importance of the study and the limitations. Chapter two (2) covers literature review which, discusses the topic of reliability assessment methods, primary bridge loadings , elastic analysis of bridge deck using ULS (Ultimate Limit State) and SLS (Serviceability Limit State) and the current practice of reliability analysis on bridge decks. Chapter three (3) presents the methodology in basic theory of reliability engineering on modeling of primary loads (HA loads) for an arbitrary bridge. Chapter four (4) would present the comparison data from reliability assessment derived from the load factor from various codes on bridge girders. The data would be tabulated and the major differences identified. The differences in result would then be related to the design aspects to ascertain which codes are permissible and which are deemed conservative.

Chapter five (5) would consist of the discussion of the results. Chapter six (6) will consist of the conclusions and appropriate recommendations.

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