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# ABSTRACT

## MULTIOBJECTIVE RELIABILITY-BASED OPTIMIZATION OF PRESTRESSED CONCRETE BEAMS

By

**Mohammed Qahtan Taha**

Under the supervision of

**Dr. Samer Barakat**

A comprehensive study on the optimal deterministic and probabilistic design of prestressed concrete beams (PCB) is presented. The Feasible Direction Method is used to obtain a set of optimal geometrical dimensions of asymmetrical I-beam cross section, and amount of prestressing steel. The bonded tendon type is considered in application of post-tensioned beam with a single duct of parabolic shape. Many parameters were analyzed including the effect of span length considering different loading cases. The performance constraints in the deterministic approach, according to the ACI 318/95 Building Code provisions, are based upon the flexural stresses, the prestressing losses, the ultimate shear strength, the ultimate moment capacity of the section with respect to cracking moment and factored loads, the crack width, the immediate deflection and the long term deflection. A practical and efficient reliability based-structural optimization (RBSO) approach is conducted to design PCB. The solution is obtained using an optimization-based program linked to a reliability analysis program. In this program, the first order second moment reliability method for the aforementioned components and systems is employed. Material properties, loading and models used to predict structural behavior at all stages, are treated as random variables. An approach of single objective RBSO (SORBO) of PCB to minimize the overall cost of the beam in terms of concrete,

prestressing steel, mild steel and formwork is given by a one-point solution. This solution does not provide enough information for decision making in the design process. Hence, the multiobjective reliability-based optimization (MORBO) of PCB is shown to be practically feasible and more beneficial than SORBO. An algorithm to handle uncertainty in MORBO problems considering the $\varepsilon$-constraint method is used and the Pareto optimum solutions are obtained. Secondary and tertiary competing objective functions have been simultaneously applied for both minimizing the overall cost and the long term deflection, as well as maximizing; the system reliability index, the reliability of flexural strength capacity, and the reliability of tensile stress at service stage. The probabilistic designs are performed using two types of target reliability index. As a result of MORBO solutions, the design charts and their interaction curves are developed. These charts can be used by the designers in selecting the best-desired solutions.

# اعتمادية التصميم الأمثل متعدد الوظائف للجيزان الخرسانية مسبقة الإجهاد

اعداد: محمـّد قحـطان طـه
اشراف: د. سـامر بركـات

## الملخص

قدّمت هذه الرسالة دراسة شاملة عن التصميم الأمثل التحديدي والاحتمالي للجيزان الخرسانية مسبقة الإجهاد، وقد استخدمت طريقة الاتجاه الممكن للحصول على مجموعة الأبعاد الهندسية للجائز لمقطع عرضي بشكل I غير متناظر وكمية من حديد التسليح المسبق الإجهاد. تمّ اعتماد حبال تسليح مسبقة الإجهاد في تصميم الجائز لاحق الشد ذو قناة مفردة من النوع المبطـّن بشكل مكافئـي المقطع، وتمّ تحليل العديد من المعاملات المتغيرة القيم المتضمّنة تأثير طول الفضاء باعتماد حالات مختلفـة مـن التحميل. إنّ قيـود الأداء ( المأخـوذة وفقـاً لشروط ومواصفات البناء الأمريكي ACI 318/95) في الطريقة التحديدية قد بنيت على اجهادات الانحناء و ضائعات قوى الإجهاد المسبق و مقاومة القـص العظمى ومقاومة المقطع للعزم الأعظم المتعلقة بعزم التشقق و عزم الأحمال المعاملة، وعرض الشق والانحراف الأولي والانحراف طـويل الأمـد. هذا وقد جرى تصميم جيزان خرسانية مسبقة الإجهاد بأتباع طريقة عملية وكفوءة، وهي طريقة التصاميم الإنشـائية المثلى المسندة بالاعتمادية، كما وجرى تطوير برامج خاصة بالامثليـة مرتبطة مع برامج أخرى لتحليل الاعتمادية من المرتبة الأولى والمستوى الثاني مع القيود أو المحددات المذكورة آنفـاً في هذه البرامج. عوملت خواص المواد و التحميـل والمعامل المستخدمـة في تنبؤ سلوك جميع المحددات والقيود أعلاه على إنـّها متغيرات عشوائيـة. لقد أعطت طريقـة الأمثليـة المسندة بالاعتمادية مفردة الهدف (SORBO) في تصميـم الجيزان الخرسـانية مسبقة الإجهاد، أعطت حلولاً وحـيدةً في تقليل الكلفة الإجمالية للجائز المتمثـّلة بكلف الخرسانة وحديد التسلـيح المسبق الإجهاد وحديد التسلـيح العادي وكلف القوالب الحديديـة، إلا أنّ هذه الحلول لم تعطي معلومات كافية لاتخاذ القرارات المناسبة أثناء عملية التصميم، وعليه، ثبت بأنّ طريقـة الأمثليـة المسندة بالاعتمادية متعـددة الأهـداف (MORBO) طريقـة عملية منطقيـّة في الحلول ذات فوائد عملية أفضل بكثير من الطريقـة مفردة الهدف. أستخدمت طريقـة القـيد المسـّماة (ε-Constraint) في حل مسائل الأمثليـة المسندة بالاعتمادية متعـددة الأهـداف والحصول على حلول باريتو (Pareto ) المثلى مع الأخذ بعين الاعتبار اللامحققـيّـة في قيم المتغيـّرات العشـوائية. كما و تمّ تطبيق أمثلة لأهداف متنافسـة ثنائية و ثلاثية متزامنـة لتقليل كل من الكلف الإجمالية للجيزان والانحراف طويل الأمد، بالإضافة إلى تطبيق أمثلة أخرى لإيصال معيار منظومة اعتمادية القيود الخاصّة بمقاومة الانحناء وكذلك اجهادات الشـد في مرحلة الخدمة إلى حدّها الأقصى. تمّ إنجاز التصاميم الاحتماليّة في تطبيق الحلول الأمثليـة المسندة بالاعتمادية متعـددة الأهـداف باستخدام نوعين من أهداف معايير الاعتمادية، وتمّ إظـّهار مخططات بيانيّة مع منحنياتها المتداخلة بحيث يمكن للمصممين استخدامها في اختيار أفضل الحلول المرغوبة.

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# CONTENTS

# LIST OF FIGURES

**Figure**

# LIST OF TABLES

**Table**

| | |
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| *Dr. Muhammad I. Rjoub, (Cognate, Al-Balqa' Applied University)* | 3-8-2000 |

*Dedication*

To the incessant fountain of giving,

*My Family*

as a token of love and gratitude

# ACKNOWLEDGMENTS

First and foremost, I would like to praise and thank Allah for his mercy and guidance, and ask him the truth and the right path.

*I greatly would like to thank the person who offered his time and effort to help me, and who continually provides me with invaluable directions and advice, my adviser, Dr. Samer Barakat. I also would like to thank my examining committee; Dr. Fayez Abdulla, Dr. Khaldoon Bani-Hani, and Dr. Muhammad I. Rjoub, for their helpful comments and suggestions. Due thanks are extended to Dr. Osama Nusair and Dr. Abdulla Malkawi for their valuable, guidance and support.*

*I owe special thanks and present deep appreciation to my father for his prayers, support and encouragement throughout my entire education. I am very grateful to my friends in Jordan, Aouf Al-Ani and Abed Al-Duleimi who made life away from home not only bearable but also enjoyable.*

Finally, I thank other friends, especially in Iraq, who directly or indirectly have helped me carry out this work.

# CONTENTS

# LIST OF FIGURES

**Figure**

# LIST OF TABLES

**Table**

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Chapter I

# INTRODUCTION

## 1.1 General

It is a well-known fact that the main goal of the structural designer is to achieve a safe, serviceable, durable, feasible, reliable, economical and aesthetically pleasing structure. Optimization techniques with reliability concepts are usually used for satisfying these necessary criteria.

Since the following concepts play a crucial role in this work, it is felt necessary to define them separately. To start with, concrete is essentially a material recognized as strong and ductile in compression, weak and brittle in tension (its strength in tension is much lower than in compression), and hence its response to external loads is improved by applying a precompression.

Prestressed Concrete (PC) is basically concrete in which internal stresses of suitable magnitude and distribution are introduced so that the stresses resulting from external loads are counteracted to a desired degree. In general, PC was adopted for the design of beams up to certain span length.

The prestressing of concrete naturally involves application of a compressive loading, prior to applying the anticipated service loads so that tensile stresses that otherwise would occur are reduced or eliminated. In prestressed concrete construction high-strength reinforcement is used. The initial tensioning of the reinforcement precompresses the surrounding concrete, giving it the ability to resist higher loads prior to cracking (Nilson, 1987).

In prestressed concrete many design variables and parameters come into play to improve the overall design. Hence, the designer can get very larger spans with small concrete sections and lighter structures by making certain improvements at the criteria under the umbrella of both serviceability and ultimate limit state categories. These criteria within the serviceability limit state category include flexural stresses in top and bottom fibers of the concrete section, cracking width, camber, deflections, whereas those within the ultimate limit state category include ultimate shear, bending and cracking strengths.

Structural engineers make attractive and important uses of optimization techniques and search for optimally designed structures. Different techniques of optimization were utilized using mathematical algorithms such as linear, integer, geometric and nonlinear programming. The algorithms for optimization process consist of two main steps, the first; analyzes the structure to find its response for carrying applied loads, whereas the second; redistributes the material. Furthermore, in these problems, there are sets of constraints that control the design under code limitations. Consequently, an optimization problem could be characterized as one in which the best solution is sought without violating its pre-fixed constraints.

In structural problems, a solution to the single objective optimal design problem is considered unique and will not provide enough information for decision making in the design process. There often exist several criteria (usually conflicting insofar as independently they would lead to different optima) to be optimized in feasible set. Multiobjective (multicriterion or vector) optimization, where a vector-valued objective functions had to be examined, is the adequate approach to this specific topic. The optimum solution of this multiobjective optimization is now given

by a set of solutions. This set is solved using the concept of Pareto optimality, which explains the optimal trade-off curves among several objective functions in graphical form.

The multiobjective optimization, therefore; offers an alternative approach to the single-objective optimization that will be based on secondary, tertiary or higher-order objectives. This alternative is preferable because it simultaneously considers all competing design objectives and results in merit values that can not be further improved without impairing some of the objectives. Later on, a decision-maker will often be faced with a choice of many alternative solutions optimizing the objective (Rao et. al., 1992).

It is now widely recognized that structural problems are nondeterministic because of the unpredictability of loads and strengths of actual structures. Therefore, problems of structural optimization must be solved in the face of uncertainty and, as a consequence, a reliability-based design philosophy should be adopted to provide finally a practical and efficient approach to the optimization of prestressed concrete beams if two or more objectives are considered.

The designed structure must have sufficient reliability against ultimate and serviceability limit states specified by the Codes. Structural failure, defined as the inability of structure to sustain the loads for which it was designed, is considered to be the ultimate limit states. Therefore, the reliability-based design process consists of proportioning the structure to satisfy requirements at ultimate limit state and then to modify the design in order to satisfy the requirements at serviceability limit state.

In this study, dead load and material properties are considered normally distributed random variables, while the live load variable is assumed to have type-I

(Gumble) distribution. Meanwhile, the imperfection in the prediction models used is taken into account by assuming random model coefficients for each limit state function.

This being the case, the design of prestressed concrete asymmetrical I-shape beam is coded into a program and coupled with reliability-based optimization programs. The set of requirements defined by the design methods and the ACI-Code (318-95) are subjected constraints besides other constraints on the shape or size of the structure.

## 1.2 Literature Review

Hundreds of researches have been published on optimization of structures during the past three and a half decades, but only a small portion of them deal with cost optimization of structures (Sarma, and Adeli, 1998). The great majority of the structural optimization researches are concerned with minimizing the weight of the structure. For concrete structures, the objective function is usually minimizing the cost. Some researchers studied other objectives in optimization of prestressed concrete structures such as; minimum amounts of prestressing steel, minimum volume of concrete, maximum girder spacing, minimum super-structure depth, maximum span-to-depth ratio, maximum feasible span length, minimum super-structure camber, and others (Sarma and Adeli, 1998).

**Cohn, and MacRaw** (1984), developed a computerized approach, OSCON program, to the optimal design of the three types of structural concrete beam, considering all relevant limit state constraints and other parametric variables. Prestressing optimization and its implications for designing simply supported

reinforced, pre or posttensioned fully or partially prestressed concrete members were considered. The problem formulation required nonlinear programming technique for its solution. The design variables consisted of six geometrical dimensions of the prismatic concrete section. The objective function was minimizing the total cost per unit length.

Later on, optimum limit design of continuous concrete beams for two and three spans (rectangular and I- shape sections) developed by **Cohn and Lounis** (1993). The study demonstrated the conflict between desirable plastic redistribution (at ultimate limit state) and zero or limited cracking (at serviceability limit state) for fully prestressed concrete structures. Optimization results suggested that partially PC structures representing the optimal prestressing degree strikes a good balance between adequate service conditions (stresses, cracking and deflection) and economy.

**Khaleel and Itani** (1993), presented a comprehensive study on the optimization of simply supported partially prestressed concrete girders using sequential quadratic programming. The design variables were the geometrical dimensions, the amount of prestressing and non-prestressing steel, and the spacing between shear reinforcement. The constraints used were based on flexural stresses, fatigue stresses, crack width, ductility, initial camber, deflection due to both live loads and dead loads, ultimate moment capacity of the section with respect to cracking moment and factored loads and ultimate shear strength.

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