UNIVERSITI PUTRA MALAYSIA

ANALYTICAL MODEL FOR PARTIALLY PRESTRESSED CONCRETE BEAM-COLUMN ELEMENTS

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By

MILAD HAFEZOLGHORANI ESFAHANI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for Degree of Doctor of Philosophy

February 2017

DEDICATION

I dedicate this thesis to my wonderful parents, Dr. Mohammad Hafezolghorani Esfahani and Dr. Mehrnoush Foroudastan for their love and supports. Without their support and faith in me, I would not be the person I am today.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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February 2017

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Nowadays, the demand for buildings and bridges with long span and light weight capable of withstanding any type of dynamic loading is increasing. The application of partially prestressing technique to reduce the yielding and damages in concrete members and structures offers an alternative solution to conventional reinforced concrete (RC) or fully prestressed concrete (FPC) approaches. Although partially prestressed concrete (PPC) has been widely used as a simple and economical construction technique for structures with medium to large span, there are no proper analytical and numerical models and detailed building code provisions for PPC elements. Besides, based on an extensive review of the literature, there is less information available about the possibility of identifying the damage in partially prestressed concrete beams and frame structures during earthquake excitation. Hence, in this study a new analytical model for PPC frame elements subjected to static and dynamic loads is developed. For this purpose, constitutive law and mathematical model for the three dimensional PPC beam-column element are formulated and a special finite element algorithm is developed. In order to develop three-dimensional nonlinear finite element formulations, the PPC frame element is represented by two nodes and an elastic element in between to reflect the elastic behavior of the member and two plastic hinges at each end of the member to reflect the inelastic behavior of the member. The elastic stiffness matrix of a three- dimensional PPC beam-column element with two nodes was developed during the present study; meanwhile, the elasto-plastic stiffness matrix of the three-dimensional PPC frame element having plastic hinges at both ends was derived using plasticity theory. Therefore, in order to detect the damages and determine the location of plastic hinges during dynamic loading in element, formulation for plasticity and yielding surface mechanism of PPC frame element is derived. A third degree polynomial using regression analysis was fitted to the results obtained from PPC section analysis to represent the mathematical model of the yield surface for each section. The developed analytical model and plasticity theory were codified and implemented in a special finite element program named ARCS3D in order to perform inelastic static and dynamic analysis for PPC structures.

In order to validate the developed analytical model, plasticity formulation and the developed FE computer program code, five conventional RC and PPC beams and frames were fabricated and tested experimentally for cyclic load using dynamic actuator. The results showed a good correlation between the numerical analysis and the experimental tests. Several parametric studies were also undertaken for low-rise, medium-rise, and high-rise partially prestressed concrete framed buildings subjected to 2D nonlinear pushover and time history analysis. Furthermore, nonlinear pushover analysis was conducted on three-dimensional four-story RC and PPC buildings. Also, 3D nonlinear dynamic time history analysis was performed on the four-story RC and PPC frame buildings subjected to multi-directional EL-Centro earthquake accelerations. The functionality and effects of PPC buildings were then interpreted from different perspectives, such as variation of displacements, peak accelerations and plastic hinge formation. The results of numerical and experimental models indicated that application of the partially prestressed concrete members in structural systems effectively increased the strength and safety of the structure during dynamic loading. Also, the developed FEM program was able to successfully identify damage occurrence in PPC structural element during applied dynamic loads. To be more specific, a comparison between results shown that the ultimate capacity, degree of flexibility and energy dissipation capacity of the PPC beam specimens improved up to 70 %, 93 % and 300 % compared to the conventional RC beam specimen. From the experimental PPC frame results, the lateral load capacity and stiffness improved up to 34 % and 17 % compared to the RC frame. Also, no crack happened in the beam of the PPC frame under super imposed dead load. Furthermore, based on the parametric studies, application of PPC members in multi-storey concrete buildings subjected to seismic loads indicated a noticeable delay in the failure process, however, conventional RC buildings collapsed at the first stage of analysis. Ultimately, this study facilitates the analysis and design procedures of the multi-story PPC and RC buildings as well as bridges in an efficient computation time which is more economical compared to normal design methods.

Abstrak tesis yang dikemukakan kepda Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

MODEL ANALATIKA BAGI UNSUR-UNSUR TIANG-RASUK KONKRIT SEPARA PRATEGASAN

Oleh

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Pada masa kini, permintaan bagi bangunan dan jambatan berentang panjang serta ringan dan mampu menahan apa jua jenis pembebanan dinamik, semakin meningkat. Penggunaan teknik prategasan separa bagi mengurangkan alahan konkrit dan kegagalan dalaman anggota konkrit dan struktur, menawarkan penyelesaian alternatif kepada teknik konvensional konkrit bertetulang (RC) atau konkrit prategasan sepenuhnya (FPC). Walaupun konkrit prategasan separa (PPC) telah digunakan secara meluas sebagai teknik pembinaan yang menjimatkan serta mudah bagi pembinaan struktur dengan rasuk rentang sederhana, juga besar, namun tiada model berangka yang sesuai dan tiada analisis yang betul digunapakai dan tiada peruntukan kod untuk unsur-unsur bangunan terperinci PPC. Selain itu, berdasarkan kajian literature yang meluas, terdapat maklumat yang kurang yang boleh didapati mengenai kemungkinan mengenal pasti kerosakan di sebahagian prategasan rasuk konkrit dan kerangka struktur semasa pengujaan gempa bumi. Oleh itu, dalam kajian ini model analisis baru untuk unsur-unsur rangka PPC tertakluk kepada beban statik dan dinamik dibangunkan. Untuk tujuan ini, undang-undang juzuk dan model matematik untuk tiga PPC dimensi unsur rasuk-tiang digubal dan algoritma unsur terhingga khas dibangunkan. Dalam usaha untuk membangunkan tiga dimensi linear rumusan unsur terhingga, elemen rangka PPC diwakili oleh dua nod dan elemen elastik di antara untuk menggambarkan kelakuan elastik anggota dan dua engsel plastik pada setiap hujung anggota untuk mencerminkan tingkah laku yang tidak boleh berubah ahli. Matriks kekukuhan anjal daripada dimensi unsur PPC rasuk-tiang tiga dengan dua nod telah dibangunkan semasa kajian ini; sementara itu, matriks kekukuhan elasto-plastik unsur rangka PPC tiga dimensi mempunyai plastik bergantung pada kedua-dua hujung diperoleh dengan menggunakan teori keplastikan. Oleh itu, untuk mengesan kerosakan dan menentukan lokasi engsel plastik semasa pembebanan dinamik dalam elemen, formulasi untuk keplastikan dan mekanisme permukaan alah elemen rangka PPC dibangunkan. Persamaan regresi menggunakan polinomial darjah ketiga telah dipadankan untuk keputusan analisa yang diperolehi daripada bahagian analisis PPC, untuk mewakili model matematik permukaan hasil untuk setiap bahagian. Analisis model dan teori keplastikan yang dibangunkan telah dimaktub dan dilaksanakan dalam program unsur terhingga khusus yang dinamakan ARCS3D untuk melaksanakan analisis statik tak elastik dan analisa dinamik untuk struktur PPC. Dalam usaha untuk mengesahkan rumusan model analisis, teori keplastikan yang dibangunkan dan kod program komputer FE, lima rasuk dan kerangka konvensional RC dan PPC telah direka dan diuji secara eksperimen untuk kenaan beban kitaran menggunakan penggerak dinamik. Hasil kajian menunjukkan korelasi yang baik antara analisis berangka dan ujian eksperimen. Beberapa kajian parametrik juga telah diambil untuk kerangka bangunan konkrit separa prategasan, bertingkat rendah, bertingkat sederhana, dan bertingkat tinggi tertakluk kepada beban mahu-mengalah 2D tak linear dan analisis sejarah masa. Tambahan lagi, analisis mahu-mengalah 2D tak linear telah dijalankan ke atas bangunan empat tingkat, tiga dimensi, RC dan PPC. Juga, analisis dinamik sejarah masa, 3D linear, telah dilakukan ke atas empat tingkat kerangka bangunan RC dan PPC tertakluk kepada daya gempa bumi pecutan pelbagai hala EL-Centro. Fungsi dan kesan bangunan PPC kemudiannya ditafsirkan dari perspektif yang berbeza, seperti perubahan anjakan, pecutan puncak dan pembentukan engsel plastik. Keputusan model berangka dan eksperimen menunjukkan bahawa penyertaan daripada anggota konkrit prategasan separa dalam sistem struktur berkesan meningkatkan kekuatan dan keselamatan struktur semasa penggenaan beban dinamik. Tambahan lagi, program FEM yang dibangunkan berjaya mengenalpasti kejadian kerosakan di elemen struktur PPC semasa beban dinamik digunakan. Untuk lebih spesifik, perbandingan antara keputusan-keputusan menunjukkan bahawa keupayaan muktamad, tahap fleksibiliti dan kapasiti tenaga pelesap daripada spesimen rasuk PPC bertambah baik sehingga 70%, 93% dan 300% berbanding dengan spesimen rasuk konvensional RC. Daripada keputusan eksperimen kerangka PPC, kapasiti beban lateral dan ketegangan meningkat sehingga 34% dan 17% berbanding dengan kerangka RC. Tambahan lagi, tiada retak berlaku dalam rasuk kerangka PPC di bawah kenaan beban galas mati. Juga, berdasarkan kajian parametrik, penggunaan elemen PPC di bangunan konkrit bertingkat dan tertakluk kepada beban seismik menunjukkan kelewatan ketara dalam proses kegagalan, bagaimanapun, bangunan RC konvensional runtuh pada peringkat pertama analisis. Akhir sekali, kajian ini memudahkan analisis dan reka bentuk prosedur bangunan PPC pelbagai tingkat dan bangunan RC serta jambatan dan membolehkan masa pengiraan yang cekap, yang lebih menjimatkan berbanding dengan kaedah reka bentuk normal.

ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude to my advisor Associate Professor Farzad Hejazi for the continuous support of my PhD study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis.

Besides, I would like to thank the rest of my supervisor committee Prof. Dato` Ir. Mohd Saleh Jaffar, Prof. Dato` Ir. Abang Abdullah Abang Ali and Ir. Dr. Voo Yen Lei, for their insightful comments and encouragement.

My sincere thanks also go to Mr. Mohammad Haffis Hamid, Mr. Muhammad Mustaqim and Mr. Zain who gave access to the structural laboratory and research facilities.

Last but not the least; I would like to thank my family, my parents and my brothers and sister for supporting me spiritually throughout writing this thesis and my life in general.

I certify that a Thesis Examination Committee has met on 16 February 2017 to conduct the final examination of Milad Hafezolghorani Esfahani on his thesis entitled "Analytical Model for Partially Prestressed Concrete Beam-Column Elements" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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CHAPTER 1

INTRODUCTION

1.1 General Overview

Prestressing concrete is a widely-used technique which was introduced in the early 1940s to overcome the natural weakness of concrete in tension (i.e. cracking and deflections) from externally applied loads. For the past two decades, the practice of prestressing tendons in prestressed beams has not been limited to bridges and industrial structures but also has been included in commercial and residential buildings. Concrete can be stressed either by pre-tensioning or post-tensioning. Pre-tensioned concrete is mostly used in prefabricated constructions, in which the members are firstly fabricated then assembled at site. As the name implies, prestressing strands are stretched before concrete hardening to ensure a full bond between concrete and prestressing strands. After releasing strands, the tensile forces in the pre-tensioned strands are transferred to the concrete until an equivalency between steel strands and concrete is achieved. This technique is mostly used to build parking structures, office buildings, stadiums and schools, and considerably decreases the total construction time and cost. On the other hand, post-tensioning strands are released after the concrete hardening. Post-tensioning would be performed using internally bonded, internally unbonded and externally unbonded tendons. Post-tensioning is mainly applied for strengthening and repair of existing structures. This method is mostly used for segmental bridges, post-tensioned slabs, continuous beams, etc. Moreover, longer spans can be achieved using post-tensioning in comparison with pre-tensioning.

The technical literature reveals that combining conventional reinforcing steels and prestressing steel strands to strengthen a flexural concrete member is normally implied by the term partially prestressed element. In current practice, partial prestressing is accepted as a technique in between full prestressing and conventional (non-prestressed) reinforcing. Prestressed strands are used to control deflections and crack widths. On the other hand, further non-prestressed reinforcement would add to the ultimate capacity without significant change in the cracking moment. In practice, partially prestressed concrete elements are employed with their design based on rational analysis, on satisfying the conditions of both serviceability and ultimate strength constraints and finally on the engineering judgment.

In comparison to reinforced concrete, with partial prestressing greater clear span with same member depth, enhanced crack control and smaller member sizes can be achieved. Moreover, steel and concrete material properties are effectively utilized.

Based on the few number of published studies, (Abeles, 1963; Hawkins, 1977; Park and Thompson, 1980; Naaman, 1986; Harajli, 1993 and 2006; Au and Du, 2004; Karayannis and Chalioris, 2013; Burgueno and Sun, 2014; Rakaa and Astawaa, 2014; Iskhakov and Ribakov, 2015) in comparison with fully prestressed concrete structures, the use of partial prestressing may enhance ductility and energy absorption capability, improve economy, as well as reduce the camber and creep deformation due to prestress. In a seismic event, the reinforcing steel will dissipate energy in a ductile manner while the post-tensioning cables along the length of the frame will provide elastic action that creates a self-righting force to pull the joint and frame back toward its original position. Although partial prestressing technique has been used in many structures, dynamically, the structural behavior of the PPC structures is yet to be well understood.

Hence, in this study a new analytical model for PPC frame elements subjected to static and dynamic loads is developed. For this purpose, constitutive law and mathematical model for the three-dimensional PPC beam-column element are formulated and a special finite element algorithm is developed. Moreover, in order to detect the damages and determine the location of plastic hinges during dynamic loading in PPC structures, formulation for plasticity and yielding surface mechanism of PPC frame element is derived. Hence, the hypothesis of the current study is development of an approach to facilitate the analysis and design procedures of multi-storey and long-span PPC buildings and bridges in an efficient computation time which is more economical in comparison with other design methods.

1.2 Brief Review of Earlier Works

Prestressed concrete members are essential in many places today in order to fully make use of concrete compressive strength and control deflection and cracking. Due to those advantages, research on the behavior of prestressed concrete members has seen impressive developments. Partially prestressed concrete structures bridge the gap between fully prestressed concrete structures and reinforced concrete structures (Allouche et Al., 1999). To be more specific, in such a structure, tension and cracking in concrete due to flexure are permitted under service dead and live loads. Hence, in the last two decades, partially prestressed techniques have been found to be attractive methods for engineers to design concrete bridges and buildings with desired form, simple and economical construction of medium to large span.

The analysis of a PPC element has additional levels of difficulty compared to the analysis of conventional reinforced concrete (RC) and fully prestressed concrete (FPC) members. On the other hand, published research on nonlinear dynamic behavior FPC and PPC structures subjected to earthquake loading is much less than conventional RC structures. Therefore, this study focuses on a new constitutive law and mathematical model for PPC frame elements subjected to static and dynamic loading. Besides, a new mathematical model for identifying the damages in partially prestressed concrete beams and frame structures during earthquake excitation is considered. Abeles (1959 and 1963) discussed partial prestressing and possibilities for its practical application. He declared the essential features, ways of approach, philosophy of design, practical application in England, and differences between fully and partially prestressing techniques. In 1977, Hawkins reviewed analytical and experimental studies related to seismic behavior of precast reinforced and fully prestressed concrete structures. Thampson and Park (1980) demonstrated that prestressed concrete has been widely used for structures carrying gravity loads but has not been as widely accepted for use in structural systems which resist seismic loading. They investigated the ductility of a few prestressed and partially prestressed concrete beams sections.

The nonlinearity of the three-dimensional nature of PPC elements was not considered during this research. Naaman et al. (1986) compared experimental data with a proposed nonlinear analytical model to evaluate the flexural ductility of PPC elements under only static loading conditions. Harajli (1993) examined only experimentally the flexural capacity of 16 PPC beam specimens strengthened by external prestressing tendons under firstly cyclic fatigue loading then, subjected to monotonically increasing load to failure. In 2006, he also presented a comprehensive assessment of the main parameters that influence the ultimate stress in un-bonded tendons and discussed the reasons behind the scatter in the predictions of test results in the literature. Au and Du (2004) explained the behavior of PPC sections under static loads. Effect of amount of steel and FRP prestressing tendons on the ductility of the bonded partially prestressed members was considered for two-dimensional static analysis sections. Karayannis and Chalioris (2013) estimated the required partial prestressing on the basis of crack control of concrete. In this study, empirical formulations (ACI318 and Euro-code 2) were used instead of developing a comprehensive analytical model. They also offered design charts and numerical paradigms for PPC rectangular and T-shape beams.

A considerable amount of work and effort was put in by Thanoon et al. (2004) and Hejazi (2010) to develop analytical and numerical methods for nonlinear behavior of conventional concrete building structures. Furthermore, formulation for plasticity and yielding surface mechanism of RC frame elements was derived in order to detect damages during dynamic loading procedure.

Due to lack of a comprehensive analytical model, plasticity theory and FE program for analysis of PPC members, ABAQUS software was utilized by Burgueno and Sun (2014) to investigate damages during manufacturing of pre-tensioned beams. Damaged plasticity analysis was conducted in the ABAQUS for this purpose.
Therefore, structural performance of PPC buildings under dynamic loads with respect to the plastic hinge formation mechanism in building components is not available.

1.3 Problem Statement

The growing use of prestressing technique for buildings and bridges with long span and light weight subjected to dynamic loads, has resulted in a need to increase the current knowledge of the behavior of PPC beam-column elements. Based on the extensive review of literature, it is observed that there is no comprehensive research on the three-dimensional seismic behavior of PPC structures. Consequently, there are crucial unresolved gaps in the understanding and assessment of PPC elements including:

i. There is no information about yield surface and plasticity theory for PPC frame elements in order to detect the damages and determine the location of plastic hinges during dynamic loading.

ii. Most of the available literature and building code provisions on the behavior of concrete members were dedicated to conventional reinforced concrete and fully prestressed concrete members. However, few researchers have focused on the two-dimensional structural behavior of PPC elements. Thus, there is no unique and specific analytical and numerical model for PPC frame elements.

iii. Modeling a simple prestressed element using existing finite element software is very complicated because all parts (i.e. concrete, normal reinforcement and prestressing steel strand) should be defined separately and then assembled. Moreover, another challenge in analyzing of PPC elements is assigning a suitable interaction between different materials, which is a time consuming procedure and requires experience. These issues increase the percentage of deviation, computation time as well as the cost of a project.

iv. According to a comprehensive review of the literature, there is lack of FE algorithm and computer program associated with a failure criteria theory to identify the exact place of damaged areas in three-dimensional prestressed structures under dynamic loads.

v. In the technical review of the literature, there is insufficient number of experimental tests available to verify and validate the structural performance of PPC beams and frame buildings under static and dynamic loads with respect to the plastic hinge formation mechanism.

1.4 Objectives of the Study

The general objective of the current study is development of a new analytical model associated with a plastic hinge formation mechanism for PPC frame elements to facilitate the seismic analysis and design procedures of multi-story PPC and RC buildings as well as bridges in an efficient computation time which is more economical in comparison with normal methods of design. Thus, specific objectives that contribute to this aim include:

1. To develop formulation for plasticity and yielding surface mechanism of PPC frame elements to detect the damages and determine the location of plastic hinges during dynamic loading.

2. To develop a new constitutive law and finite element model for PPC frame elements.

3. To formulate and develop a new FEM algorithm and subsequently implement it in the FE program package in order to perform nonlinear static and dynamic analysis of PPC structures, and validating the FE program by conducting sufficient number of experimental tests.

1.5 Scope and Limitation of Work

To ensure that the above objectives are achieved, the present study is organized as follows:

1) In the current study, constitutive law and mathematical model for beam-column elements are considered.

2) Three-dimensional finite element formulations are implemented for beam-column elements.

3) In the numerical analysis, nonlinear characteristics of all material are considered.

4) 3D yielding surface and plasticity mechanism for PPC frame elements is implemented.

5) Newmark's systematic step-by step integration approach has been chosen for nonlinear analyses. Computation strategies are presented for the predication of time history response.

6) Experimental tests are conducted to validate the developed formulations and plasticity theory.

Furthermore, limitations of the present study are presented as follows:

1) Effects of prestress losses are not considered in finite element formulations.

2) Un-bonded prestressed technique is not considered in this study.

3) Effect of tensile strength in concrete is also not considered.

1.6 Organization of the Thesis

The thesis comprises five chapters and the summaries of these chapters are provided below.

The significance and definition of the problem statement of the present investigation have been highlighted in Chapter 1 along with the objectives and scope of the study.

Chapter 2 reviews relevant previous studies in the literature about analytical model, inelastic analysis, finite element formulations, yielding surface and hinge formation as well as experimental tests which have been done related to RC, FPC and PPC elements and structures.

The detailed methodology of this study is discussed in Chapter 3. Formulation of plasticity and yielding surface mechanism of PPC frame element and its development is presented. Also, development of 3D nonlinear PPC frame elements and finite element procedure for nonlinear static and dynamic analysis is derived. Development of numerical computation procedure and computer program code

A general description of the test specimens, material properties, instrumentation arrangements and loading procedure of experimental tests are explained in Chapter 4.

Chapter 5 extensively reports the comparison between numerical and experimental results of conventional reinforced concrete and PPC beam and frame specimens under flexural and cyclic analysis in order to validate the developed analytical model, plasticity formulation and the developed FE computer program code. In addition, seismic performance assessment of multi-story PPC structures is investigated under severe superimposed dead and live loads.

Chapter 6 summarizes the present study and provides its major and specific conclusions. The scope of future works and recommendations are also discussed.

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