UNIVERSITAT POLITÈCNICA DE CATALUNYA

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SHEAR DESIGN OF REINFORCED HIGH-STRENGTH CONCRETE BEAMS

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ABSTRACT

Although High-Strength Concrete has been increasingly used in the construction industry during the last few years, current Spanish Structural Concrete code of practice (EHE) only covers concrete of strengths up to 50 MPa. An increase in the strength of concrete is directly associated with an improvement in most of its properties, in special the durability, but this also produces an increase in its brittleness and smoother crack surfaces which affects significantly the shear strength.

The aim of this research is to enhance the understanding of the behaviour of high-strength concrete beams with and without web reinforcement failing in shear. In order to achieve this objective, an extensive review of the state-of-the-art in shear strength for both normal-strength and high-strength concrete beams was made, as well as in-depth research into previous experimental campaigns.

An experimental programme involving the testing of eighteen high-strength beam specimens under a central point load was performed. The concrete compressive strength of the beams at the age of the tests ranged from 50 to 87 MPa. Primary design variables were the amount of shear and longitudinal reinforcement. The results obtained experimentally were analysed to study the influence of those parameters related to the concrete compressive strength.

With the aim of taking into account, in addition to the results of our tests, the large amount of information available, a large database was assembled based on the University of Illinois Sheardatabank for normal-strength and high-strength concrete beams. These test results were compared with failure shear strengths predicted by the EHE Code, the 2002 Final Draft of EuroCode 2, the AASHTO LRFD Specifications, the ACI Code 318-99, and Response-2000 program, a computer program based on the modified compression field theory.

Furthermore, two Artificial Neural Networks (ANN) were developed to predict the shear strength of reinforced beams based on the database beam specimens. An ANN is a computational tool made up of a number of simple, highly-interconnected processing elements that constitute a network. The main feature of an ANN is its ability to learn, by means of adjusting internal weights, even when the input and output data present a degree of noise. Based on the ANN results, a parametric study was carried out to study the influence of each parameter affecting the failure shear strength.

New expressions are proposed, taking into account the observed behaviour for the design of high-strength and normal-strength reinforced concrete beams with and without web reinforcement. A new equation is given for the amount of minimum reinforcement as well. The new expressions correlate with the empirical tests better than any current code of practice.

Finally, as a natural corollary to the evolution of our understanding of this field, some recommendations for future studies are made.

RESUMEN

Aunque el hormigón de alta resistencia se está utilizando de manera creciente en los últimos años para la construcción de estructuras, la norma Española vigente, la Instrucción EHE, sólo abarca hormigones de resistencias características a compresión inferiores a 50 MPa. El aumento de resistencia del hormigón está directamente asociado a una mejora en la mayoría de sus prestaciones, especialmente de la durabilidad, aunque también produce un aumento en la fragilidad y una disminución de la rugosidad de las fisuras, lo que afecta de forma muy especial a la resistencia a cortante.

El objetivo principal de este trabajo es contribuir al avance del conocimiento del comportamiento frente a la rotura por cortante de vigas de hormigón de alta resistencia. Para ello, y en primer lugar, se ha llevado a cabo una extensa revisión del estado actual del conocimiento de la resistencia a cortante, tanto para hormigón convencional como para hormigón de alta resistencia, así como una profunda investigación de campañas experimentales anteriores.

Se ha realizado una campaña experimental sobre vigas de hormigón de alta resistencia sometidas a flexión y cortante. La resistencia a compresión del hormigón de las vigas variaba entre 50 y 87 MPa. Las principales variables de diseño eran la cuantía de armadura longitudinal y transversal. Los resultados obtenidos experimentalmente han sido analizados para estudiar la influencia de las distintas variables en función de la resistencia a compresión del hormigón.

Con el objetivo de tener en cuenta, no sólo los resultados de nuestros ensayos, sino también la gran cantidad de información disponible en la bibliografía técnica, se ha preparado una base de datos con vigas de hormigón convencional y de alta resistencia a partir del banco de datos de la Universidad de Illinois. Los resultados empíricos han sido comparados con los cortantes últimos calculados según la Instrucción EHE, las especificaciones AASHTO LRFD, el Código ACI 318-99 y el programa Response-2000, basado en la teoría modificada del campo de compresiones.

Se han construido dos Redes Neuronales Artificiales (RNA) para predecir la resistencia a cortante en base a la gran cantidad de resultados experimentales. La principal característica de las RNA es su habilidad para aprender, mediante el ajuste de pesos internos, incluso cuando los datos de entrada y salida presentan un cierto nivel de ruido. Con los resultados de la RNA se ha realizado un análisis paramétrico de cada variable que afecta la resistencia última a cortante.

Se han propuesto nuevas expresiones que tienen el cuenta el comportamiento observado para el diseño frente al esfuerzo cortante de vigas tanto de hormigón convencional como de alta resistencia con y sin armadura a cortante, así como una nueva ecuación para la determinación de la armadura mínima a cortante. Las nuevas expresiones presentan resultados que se ajustan mejor a los resultados experimentales que los obtenidos mediante la utilización de las normativas vigentes.

Finalmente se han planteado varias sugerencias de futuras líneas de trabajo, que son resultado de la propia evolución del conocimiento sobre el tema de estudio durante el desarrollo de esta tesis.

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Chapter 1

Introduction

The use of High-Strength Concrete (HSC) has increased considerably during the last decade, since it can be produced reliably in the field using low water-cement ratios thanks to high-quality water-reducing admixtures. Furthermore, HSC will be more and more frequently used in columns, in precast elements and in structures where durability is an important design parameter.

To give a simplified explanation, HSC is obtained by improving the compactness of the concrete mix, which increases the strength of both the paste and the interface between the paste and the coarse aggregate. However, an increase in the strength of the concrete produces an increase in its brittleness and smoother shear failure surfaces, leading to some concerns about the application of high-strength concrete. Since most of the current shear procedures are based on tests carried out on beams with a concrete compressive strength lower than 40 MPa, and one of the shear transfer mechanism is shear-friction across the cracks, the failure shear strength needs to be re-evaluated.

Moreover, despite the more and more frequent utilisation of high-strength concrete in Spain, the current Spanish code of practice, the EHE Code, only covers concrete of strengths up to 50 MPa, although it gives some recommendations for the use of HSC in its Annex 11. For this reason, in 1999, the Spanish Ministry of Science and Technology launched the project entitled “Design basis of high-strength reinforced concrete structural elements - CICYT-TRA99/0974”[†] directed by Professor Antonio R. Marí Bernat and with the collaboration of the companies ALVISA and TEC’4. The research described in this thesis was included in this project and its main objective was to determine the shear strength at failure of structural high-strength concrete members.

1.1 Objectives of the Thesis

The prime objective of this research is to improve the understanding of the behaviour of high-strength reinforced concrete elements failing in shear, helping to extend the use of this material in Spain. Furthermore, we intend to develop more accurate procedures for predicting the shear strength of these elements.

In order to achieve these general aims, the following specific objectives are proposed:

- To contribute to the understanding of the mechanism of shear strength in reinforced concrete beams with or without shear reinforcement and how the use of high-strength concrete may affect them.

- To study the shear-loading capacity of full-scale high-strength concrete elements specially designed to be able to evaluate the influence of different parameters on the failure shear strength.

- To evaluate the performance of the shear procedures laid down in different code of practice for normal-strength and high-strength concrete beams.

- To propose a simplified shear design method for predicting the failure shear strength for both normal-strength and high-strength concrete beams, including a proposal for the minimum amount of transverse reinforcement.

[†] *Original title:* “Establecimiento de bases de cálculo y criterios de proyecto de elementos estructurales de hormigón de alta resistencia para infraestructuras viarias y ferroviarias”

1.2 Structure of the Thesis

The thesis is divided into seven chapters. In Chapter 2 a state of the art is presented, in which different conceptual models and shear design procedures for evaluating the failure shear strength of reinforced concrete beams with and without web reinforcement are introduced. Moreover, the basic characteristics of high-strength concrete are pointed out and previous experimental research is summarised.

In order to better understand the response of high-strength concrete beams that fail in shear, eighteen beam specimens are designed in Chapter 3. The details of beam specimens, material properties, instrumentation and the testing procedure used are carefully described.

The results obtained from the experimental campaign carried out at the Structural Technology Laboratory of the Technical University of Catalonia (UPC) are presented and discussed in Chapter 4. The influence of each design parameter is studied separately, and test results are compared with different shear approaches.

Chapter 5 compares the experimental results obtained in 316 beams tested in different laboratories around the world with the failure shear strength predicted by the EHE code, the Final Draft of Eurocode 2, the AASHTO LRFD Specifications, the ACI Code 318-99, and the program Response 2000, based on the Modified Compression Field Theory. Furthermore, two Artificial Neural Networks that were used to predict the empirical results and a parametric study carried out based on the Artificial Neural Network predictions are both described in detail.

A new shear design method based on the observed behaviour is proposed in Chapter 6 for normal-strength and high-strength reinforced concrete beams with and without web reinforcement, attempting, however, to keep it simple enough to make it suitable for implementation in a code of practice.

Finally, Chapter 7 presents general and specific conclusions, together with recommendations for future research.

Annexes A to E give further information of the test results, experimental database, weights and biases of the Artificial Neural Networks and other relevant data.