



**UNIVERSITAT POLITÈCNICA DE CATALUNYA**

Departament d'Enginyeria de la Construcció

# **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 en 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.





# Contents

<b>Abstract</b> .....	i
<b>Resumen</b> .....	iii
<b>Contents</b> .....	v
<b>List of Figures</b> .....	xi
<b>List of Tables</b> .....	xvii
<b>1. Introduction</b> .....	<b>1</b>
1.1 Objectives of the Thesis .....	1
1.2 Structure of the Thesis .....	2
<b>2. State of the art</b> .....	<b>5</b>
2.1 Introduction to the High Strength Concrete (HSC) .....	6
2.2 Shear strength in concrete beams without web reinforcement .....	9
2.2.1 Mechanisms of shear transfer .....	9
2.2.2 Historical development .....	12
2.2.2 Code review .....	17
Spanish Code EHE-99	
Eurocode 2: Final Draft April 2002	
AASHTO LRFD 2000	
ACI Code 318-99	
2.3 Shear strength in concrete beams with web reinforcement .....	21
2.3.1 Forces in a member with web reinforcement .....	21
2.3.2 Historical development .....	22
2.3.3 Truss models .....	27
2.3.4 The Modified Compression Field Theory .....	30
2.3.5 Truss Models vs. Modified Compression Field Theory .....	36
2.3.6 Code review .....	38
Spanish Code EHE-99	
Eurocode 2: Final Draft April 2002	
AASHTO LRFD 2000	
ACI Code 318-99	

2.4	Shear strength in high strength concrete beams .....	40
2.4.1	Introduction .....	40
2.4.2	Minimum web reinforcement .....	42
2.4.3	Shear strength in HSC beams without web reinforcement ..	44
2.4.4	Shear strength in HSC beams with web reinforcement .....	46
2.5	Conclusions of the state-of-the-art .....	47
<b>3. Experimental Program</b>		<b>49</b>
3.1	Objectives of the Experimental Campaign .....	49
3.2	Design of the Test Specimens .....	50
3.3	Specimen Details .....	54
3.3.1	Material Properties .....	54
3.3.2	Fabrication of the Test Specimens .....	56
3.4	Instrumentation .....	56
3.4.1	Series H60 and H70 .....	58
3.4.2	Series H50 and H100 .....	59
3.4.3	Data acquisition system .....	60
3.5	Testing Procedure .....	61
3.5.1	Test Configuration .....	61
3.5.2	Loading Procedure .....	62
<b>4. Test results and discussion</b>		<b>65</b>
4.1	Introduction to Experimental Results .....	65
4.2	Modes of failure .....	67
4.3	Beam specimens without web reinforcement .....	69
4.4	Beam specimens with stirrups .....	71
4.4.1	Specimens with the proposed minimum amount of web reinforcement .....	71
4.4.2	Influence of the concrete compressive strength .....	73
4.4.3	Influence of the amount of shear reinforcement .....	75
4.4.4	Influence of the amount of longitudinal reinforcement .....	81
4.5	Beam specimens with distributed longitudinal reinforcement .....	82
4.6	Comparison of test results with different code approaches .....	84
4.7	Conclusions of the test results .....	85

<b>5. Analyses of 320 beam tests. Application of Artificial Neural Networks.</b>	<b>89</b>
5.1 Introduction to the Experimental Database .....	89
5.2 Verification of different shear procedures .....	90
5.2.1 EHE Code .....	99
5.2.2 Eurocode 2: April 2002 Final Draft .....	100
5.2.3 AASHTO LRFD 2000 .....	101
5.2.4 ACI Code 318-99 .....	102
5.2.5 Response-2000 .....	103
5.3 Introduction to Artificial Neural Networks .....	104
5.3.1 Human Neural Network vs Artificial Neural Networks .....	105
5.3.2 Building an Artificial Neural Network .....	107
5.3.3 Learning process – Back propagation .....	110
5.3.4 Data selection and pre-processing training data .....	113
5.4 Artificial Neural Networks for members not containing shear reinforcement .....	114
5.4.1 Data selection .....	114
5.4.2 Topology of the ANN, learning process and validation .....	115
5.4.3 Parametrical analyses based on the ANN results .....	118
Size effect. Influence of the effective depth $d$ .	
Influence of the concrete compressive strength $f_c$ .	
Influence of the amount of longitudinal reinforcement.	
Influence of the $a/d$ ratio	
5.5 Artificial Neural Networks for members containing shear reinforcement .....	123
5.5.1 Data selection .....	123
5.5.2 Topology of the ANN, learning process and validation .....	124
5.5.3 Parametrical analyses based on the ANN results .....	126
Influence of the amount of web reinforcement	
Size effect. Influence of the effective depth, $d$ .	
Influence of the concrete compressive strength, $f_c$ .	
Influence of the amount of longitudinal reinforcement.	
Influence of the $a/d$ ratio	
5.6 Conclusions of the analyses of 316 beam specimens .....	132

<b>6. Proposal for a new shear design method</b>	<b>133</b>
6.1 Beams without web reinforcement .....	133
6.1.1 Summary of the observed behaviour .....	133
6.1.2 Shear design method .....	134
6.1.3 Simplified shear design method .....	136
6.1.4 Verification of the proposed equations using the experimental database .....	137
6.1.5 Verification of the proposed equations for elements with longitudinal distributed reinforcement .....	140
6.2 Beams with web reinforcement .....	141
6.2.1 Summary of the observed behaviour .....	141
6.2.2 General shear design method: procedure and justification .	142
Procedure	
Justification	
6.2.3 Simplified shear designing method.....	145
6.2.4 Simplified shear verification method.....	145
6.2.5 Verification of the proposed equations with the experimental database .....	146
6.2.6 Equivalence between the simplified shear design method and the simplified shear verification method .....	149
6.3 Comparison of the propose methods with beams tested at the Structural Technology Laboratory .....	150
 <b>7. Conclusions</b>	 <b>153</b>
7.1 Specific conclusions .....	154
7.1.1 Conclusions based on the test results .....	154
7.1.2 Conclusions based on the analyses of 316 test beams .....	155
Conclusions for beams without web reinforcement	
Conclusions for beams with stirrups	
7.1.3 Conclusions based on the proposed shear design procedures .....	158
Members without web reinforcement	
Members with web reinforcement	
7.2 Recommendations for future studies .....	159

## **ANNEXES**

Annex A: Experimental Results

Annex B: Material Properties

Annex C: Experimental Database

Annex D: Artificial Neural Networks. Weights and biases

Annex E: Non Linear Finite Element Analyses



# List of Figures

2.1	B-regions and D-regions (Schlaich et al ,1987) .....	6
2.2	Arch action in a beam .....	6
2.3	Two Union Square Centre, Seattle .....	7
2.4	Montjuïc pedestrian bridge, Barcelona .....	7
2.5	Typical stress-strain relationships for high-strength concrete .....	8
2.6	Principal stress-strain curves for cement paste, aggregates and concrete in compression .....	8
2.7	Internal forces in a cracked beam without stirrups .....	10
2.8	Walraven's model of crack friction .....	10
2.9	Predicted and observed strengths of a series of reinforced concrete beams tested by Kani .....	11
2.10	Principal compressive stress trajectories in an uncracked beam and photograph of a cracked reinforced concrete beam .....	12
2.11	Shear stress distribution in a reinforced concrete beam with flexural cracks	13
2.12	Kani's comb model for cracked beams subjected to shear .....	13
2.13	Influence of member depth and maximum aggregate size on shear stress at failure .....	14
2.14	Values of $\beta$ and $\theta$ for sections without shear reinforcement .....	20
2.15	Internal forces in a cracked beam with stirrups .....	21
2.16	Ritter's truss model .....	22
2.17	Morsch truss analogy .....	23
2.18	Wilkins Air Force Depot in Shelby, Ohio .....	23
2.19	MCFT: average stresses and stresses at a crack .....	26
2.20	Equilibrium conditions for variable-angle truss .....	27
2.21	Flow of diagonal compressive force in cross sections of wide beams .....	29
2.22	Equilibrium in terms of Average Stresses .....	32
2.23	Compatibility in terms of Average Strains .....	32
2.24	Compressive stress-strain relationships for cracked concrete .....	34
2.25	Average stress-strain relationship for concrete in tension .....	34
2.26	Equilibrium in terms of local stresses at a crack .....	35
2.27	Parameters influencing crack spacing .....	35

2.28	MCFT- Average stresses and stresses at a crack .....	36
2.29	Values of $\beta$ and $\theta$ for sections containing at least the minimum amount of shear reinforcement (AAHTO LRFD Specifications) .....	40
2.30	Crack in high-strength concrete .....	41
2.31	Comparison of minimum web reinforcement provisions .....	43
3.1	Test set-up and cross-section of the beam specimens .....	51
3.2	Comparison of minimum amount of web reinforcement and proposed equation .....	52
3.3	Comparison of the compression failure of H50 and H100 concrete cylinders .....	55
3.4	Typical stress-strain curves for web reinforcing steel .....	55
3.5	Specimens fabrication in the precast plant Alvisa in Selgua (Huesca, Spain) .....	57
3.6	Location of the Temposonic Transducers for load-deflection measuring ....	58
3.7	Typical strain gauge location for beam specimens H60 and H75 .....	58
3.8	Strain gauge rosette in the concrete web for beam specimens H60 and H75 .....	59
3.9	Typical strain gauge location for beam specimens H50 and H100 .....	59
3.10	Calculation of the shear strain $\gamma_{xy}$ from Mohr's circle .....	60
3.11	Rosette of Temposonic transducers to measure the shear deformation .....	60
3.12	Test configuration .....	61
3.13	Details of the supporting beam and bearings .....	62
4.1	Cracking prior to failure and at failure in a beam with web reinforcement. Concrete spalling near the diagonal crack .....	68
4.2	Typical crack patterns at failure in the tested beams .....	68
4.3	Beam specimens without web reinforcement. Influence of the concrete compressive strength .....	69
4.4	Beam specimens without web reinforcement. Comparison of the final state of cracking in beams H50/1 (a) and H100/1 (b) .....	70
4.5	Beam specimens without web reinforcement. Crack surface in beam H100/1. Crack goes through aggregates .....	70
4.6	Beam specimens without web reinforcement. Load-deflection response for beam specimens without shear reinforcement .....	71
4.7	Shear deformation in beams without shear reinforcement and with the minimum amount proposed .....	73



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4.8	Crack pattern at failure for test beams with the proposed minimum amount of web reinforcement .....	73
4.9	Beam specimens with web reinforcement. Failure shear strength vs. concrete compressive strength for series 3 and 4 .....	74
4.10	Beam specimens with web reinforcement. Load-deflection response for series 3 beam specimens .....	74
4.11	Influence of the amount of shear reinforcement. Failure shear stress of beams H50/1, H50/2, and H50/3 .....	75
4.12	Influence of the amount of shear reinforcement. Shear strain of beams H50/1, H50/2, and H50/3 .....	76
4.13	Influence of the amount of shear reinforcement. Crack pattern at failure for beams H50/1, H50/2, and H50/3 .....	76
4.14	Influence of the amount of shear reinforcement. Stirrup strains for beams H50/2 and H50/3 .....	77
4.15	Influence of the amount of shear reinforcement. Failure shear stress of beams H60/1, H60/2, and H60/3 .....	78
4.16	Influence of the amount of shear reinforcement. Final state of cracking in the critical shear span for beams H60/1, H60/2, and H60/3 .....	78
4.17	Influence of the amount of shear reinforcement. Failure shear stress of beams H75/1, H75/2, and H75/3 .....	79
4.18	Influence of the amount of shear reinforcement. Crack pattern development of beams H75/2 and H75/3 .....	80
4.19	Influence of the amount of shear reinforcement. Failure shear stress of beams H100/1, H100/2, and H100/3 .....	81
4.20	Influence of the amount of longitudinal reinforcement. Longitudinal reinforcement strains for beams H50/3 and H50/4 .....	82
4.21	Beam specimens with distributed longitudinal reinforcement. Shear strain of beams H50/5 and H100/5 .....	83
4.22	Beam specimens with distributed longitudinal reinforcement. Final cracking state for beams specimens H50/5 and H100/5 compared to specimens H50/1 and H100/1 .....	83
4.23	Summary of predictions by EHE-99, Eurocode 2, AASHTO LRFD, ACI Code 318-99, and Response-2000 program .....	86

---

5.1	Verification of different code procedures. $(V_{\text{test}}/V_{\text{pred}})_{1\%}$ and $(V_{\text{test}}/V_{\text{pred}})_{99\%}$ for members without web reinforcement .....	95
5.2	Verification of different code procedures. $(V_{\text{test}}/V_{\text{pred}})_{1\%}$ and $(V_{\text{test}}/V_{\text{pred}})_{99\%}$ for members with web reinforcement .....	95
5.3	Verification of different shear design procedures. Demerit points for beams without web reinforcement .....	96
5.4	Verification of different shear design procedures. Demerit points for beams with web reinforcement .....	97
5.5	Correlation of the EHE procedure with empirical tests .....	99
5.6	Correlation of the EC-2 procedure with empirical tests .....	100
5.7	Comparison of shear procedures with empirical results for members with web reinforcement .....	101
5.8	Correlation of the AASHTO LRFD shear procedure with empirical tests ...	102
5.9	Correlation of the ACI Code shear procedures with empirical tests for beams without web reinforcement .....	103
5.10	Correlation of the Response 2000 predictions with empirical tests .....	104
5.11	Typical neural network model .....	105
5.12	Human neuron. An artificial neuron tries to reproduce its three main parts .	106
5.13	Sigmoid transfer function .....	108
5.14	Example of an over-fitted network vs. a well-trained network .....	109
5.15	Typical learning curves showing the error on training and testing sets .....	112
5.16	Artificial Neural Network for beams without web reinforcement. Learning process for network with 10 hidden units .....	116
5.17	Artificial Neural Network for beams without web reinforcement. Correlation with 30 unseen empirical beams (validating set) .....	117
5.18	ANN results compared to EHE and ACI 11-3 predictions for beams without web reinforcement. Size effect related to the concrete compressive strength .....	119
5.19	ANN results compared to the predictions made by Fujita's method and the method proposed in this section for beams without web reinforcement. The size effect as related to the concrete compressive strength .....	119
5.20	ANN results compared to the predictions made by the EHE and the method proposed in this section for beams without web reinforcement. Influence of the concrete compressive strength as related to the size effect	121

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---

5.21	ANN results as compared to the predictions made by the EHE and the method proposed in this section for beams without web reinforcement. Influence of the amount of longitudinal reinforcement .....	122
5.22	ANN results as compared to the EHE and CM-90 predictions for beams without web reinforcement. Influence of the a/d ratio .....	123
5.23	ANN results as compared to the EHE, EC-2 and AASHTO predictions for beams with web reinforcement. Influence of the amount of shear reinforcement in relation to the concrete compressive strength .....	127
5.24	ANN results as compared to the EHE, EC-2 and AASHTO predictions for beams with web reinforcement. Size effect in relation to the amount of shear reinforcement .....	128
5.25	ANN results as compared to the EHE, EC-2, and AASHTO predictions for beams with web reinforcement. Influence of the concrete compressive strength in relation to the beam size .....	129
5.26	ANN results as compared to EHE, EC-2, and AASHTO predictions for beams with web reinforcement. Influence of the concrete compressive strength related to the amount of transverse reinforcement .....	130
5.27	ANN results as compared to the EHE, EC-2 and AASHTO predictions for beams with web reinforcement. Influence of the amount of longitudinal reinforcement .....	131
5.28	ANN results compared to EHE, EC-2, and AASHTO predictions for beams with web reinforcement. Influence of the moment/shear (M/V) relationship .....	131
6.1	Proposed size effect in function of the concrete compressive strength .....	135
6.2	Value of $s_x$ for members without web reinforcement .....	135
6.3	Correlation of the proposed equations with empirical tests for beams without web reinforcement .....	139
6.4	Longitudinal strain in the web .....	144
6.5	Correlation of the proposed equations with empirical tests for beams with web reinforcement .....	149
6.6	Correlation between the simplified shear design method (§6.2.3) and the simplified shear verification method (§6.2.4) .....	150

---



# List of Tables

3.1	Details of beam specimens .....	53
3.2	Composition of four concretes .....	54
3.3	Properties of web reinforcing bars .....	55
3.4	Loading procedure and test duration .....	63
4.1	Summary of experimental results .....	66
4.2	Minimum amount of web reinforcement, observed failure, yielding and cracking shear for each specimen .....	72
4.3	Summary of predictions by EHE-99, Eurocode 2, AASHTO LRFD, ACI Code 318-99, and Response-2000 program .....	85
5.1	Summary of beams in database .....	91
5.2	Verification of shear procedures with full database .....	93
5.3	Demerit points classification .....	96
5.4	Verification of different code procedures using partial sets of the database .....	98
5.5	Artificial Neural Networks for beams without web reinforcement. Ranges of parameters in the database .....	114
5.6	Artificial Neural Networks for beams without web reinforcement. Training and validating sets .....	115
5.7	Artificial Neural Network for beams without web reinforcement. Verification using partial sets of the database .....	117
5.8	Artificial Neural Networks for beams with web reinforcement. Ranges of parameters in the database .....	124
5.9	Artificial Neural Networks for beams with web reinforcement. Training and validating sets .....	124
5.10	Artificial Neural Network for beams with web reinforcement. Verification using partial sets of the database .....	125
6.1	Verification of proposed shear procedures using the entire database for beams without web reinforcement .....	137
6.2	Comparison of Demerit Points classifications for beams without web reinforcement .....	138
6.3	Verification of different code procedures using partial sets of the database for beams without web reinforcement .....	139

6.4	Summary of predictions by EHE, AASHTO LRFD, equation 6.1 and equation 6.3 for elements with longitudinal distributed reinforcement .....	141
6.5	Verification of proposed shear procedures for beams with web reinforcement using the entire database .....	146
6.6	Comparison of Demerit Points classifications for beams with web reinforcement .....	147
6.7	Verification of different code procedures using partial sets of the database for beams with web reinforcement .....	147
6.8	Comparison of the proposed general and simplified shear procedures and current codes with test results of the experimental campaign .....	151

# 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”<sup>†</sup> directed by Professor Antonio R. Mari 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.

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<sup>†</sup> *Original title:* “Establecimiento de bases de cálculo y criterios de proyecto de elementos estructurales de hormigón de alta resistencia para infraestructuras viarias y ferroviarias”

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## **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.