Chapter 7

Conclusions

The main purpose of the research reported in this thesis was to improve the understanding of the behaviour of high-strength reinforced concrete beams failing in shear. In general, both the principal and specific objectives as indicated in Chapter 1 have been met.

The mechanism of shear transfer for reinforced concrete beams with and without web reinforcement was carefully described in this thesis, and different approaches to shear design were introduced chronologically. Moreover, the main differences in shear strength between high-strength and normal-strength concrete beams were highlighted together with many experimental campaigns carried out in previous years. Although an effort was made to refer to all the fundamental works, some important papers may have been unconsciously omitted.

To fully understand the behaviour of high-strength concrete beams failing in shear, eighteen beam specimens were tested. The specific conclusions of the tests are presented in §7.1.1.

Two Artificial Neural Networks were satisfactorily trained to predict the shear strength of reinforced concrete members. Based on their results, a parametric study was carried out in order to revise the influence of the parameters affecting the shear strength. The most important conclusions drawn from these analyses are presented in §7.1.2.

Finally, new general shear design procedures and simplified methods for normal-strength and high-strength reinforced concrete beams with and without web reinforcement were presented in Chapter 6. In §7.1.3 the main conclusions drawn from the proposals are summarised.

7.1 Specific conclusions

7.1.1 Conclusions based on the test results

Based on the results of the eighteen beam specimens tested at the Structural Technology Laboratory of the Technical University of Catalonia (UPC) the following conclusions were drawn:

- High-strength concrete beams without web reinforcement presented a very fragile behaviour. The higher the concrete compressive strength, the brisker the failure. On the other hand, high-strength concrete beams with stirrups exhibited a less brittle response.

- For beams without web reinforcement, the failure shear strength generally increased as the concrete compressive strength increased. This effect was more evident in beams with web reinforcement.

- The minimum amount of web reinforcement proposed in §3.2 prevented a sudden shear failure upon the formation of the first diagonal tension crack, and was sufficient in terms of reserve of strength.

- The higher the concrete compressive strength, the more effective stirrups were.

- For the beam tests, limiting the amount of longitudinal reinforcement to 2% was not experimentally justified.

- Beam specimens with longitudinally distributed web reinforcement along the web behaved better than similar beams without any kind of shear reinforcement. Although failure was also fragile, several shear cracks were reported, and the failure shear strength increased by about 25%.

- The EHE shear procedure gave a satisfactory correlation for beams without web reinforcement. However, for beams with stirrups it was too conservative.

- The April 2002 Final Draft of Eurocode 2 was unconservative for beams without web reinforcement. On the other hand, it performed too conservatively for beams with stirrups.

- The AASHTO LRFD Specifications, based on the modified compression field theory, correlated very well with the empirical results compared with the other codes' procedures.

- The computer program Response-2000, also based on the modified compression field theory, performed satisfactorily, yielding a very low coefficient of variation.

7.1.2 Conclusions based on the analyses of 316 test beams

Conclusions for beams without web reinforcement

Based on the statistical analyses carried out to compare different code approaches, the following conclusions were drawn:

- The EHE and AASHTO shear procedures generally performed very similarly and correctly predicted the shear strength of beams without web reinforcement, although their procedures are entirely different.

- The EHE procedure is more conservative for high-strength concrete beams than for normal-strength concrete beams.

- Concrete beams with low flexural reinforcement presented a lower safety factor than highly reinforced beams using the EHE shear procedure.

- Although the size effect is taken into account in the EHE procedure, the predictions for deep beams (d ≥ 900 mm) were less conservative than for the average. For very small beams (d ≤ 100 mm) EHE predictions were unconservative.

- The 2002 Final Draft of Eurocode 2 was unconservative for deep beams and for low reinforced beams.

- The ACI 11-3 equation (and therefore Spanish EH-91 shear procedure) was also unconservative for deep beams and beams with low longitudinal reinforcement.

Based on the Artificial Neural Network model, it was concluded that:

- Artificial Neural Networks have been shown to be a powerful tool for predicting the shear strength of reinforced concrete beams. The average V_{test}/V_{pred} ratio was 0.99 for the training set and 1.02 for the validating set. The coefficients of variation were 12.79% and 12.53% respectively.

- Size effect was related to the concrete compressive strength. For deep beams, the benefit of a higher concrete compressive strength was outweighed by the loss caused by the size effect.

- The influence of the amount of longitudinal reinforcement was higher than that suggested by the EHE procedure, and it is proposed in this thesis to limit it to 2-4% (depending on the concrete compressive strength) instead of the 2% specified by the current code.

- The shear span-to-depth ratio, a/d, influenced the failure shear strength although all beams showed an a/d greater than 2.5.

Conclusions for beams with stirrups

Based on the statistical analyses carried out for beams with web reinforcement, the following conclusions were drawn:

- The EHE code was in general excessively conservative for beams with web reinforcement. However, for beams with a high amount of shear reinforcement it might be unconservative.

- The 2002 Final Draft of Eurocode 2 gave the worst predictions compared with the experimental results. For low shear reinforced members it was too conservative, and for highly reinforced shear beams it was clearly unconservative.

- The AASHTO LRFD shear procedure generally showed a good correlation with the test results, being slightly unconservative only for members with a low amount of longitudinal reinforcement.

Based on the Artificial Neural Network model, it was concluded that:

- Artificial Neural Networks were again a powerful tool for predicting the shear strength of concrete beams. The average V_{test}/V_{pred} ratio was 1.00 for the training set and 1.01 for the validating set. The coefficient of variation were 10.96% and 13.38% respectively.

- The influence of the amount of web reinforcement was not linearly proportional to the failure shear strength. The more stirrups, the less effective they were.

- For members with low shear reinforcement, the size effect reduced the failure shear stress by about 25% as effective depth was increased from 250 to 700 mm.

- The influence of the concrete compressive strength varied with the amount of transversal reinforcement and the size of the beam. Generally speaking, however, the higher the concrete compressive strength the higher the failure shear strength.

- The influence of the amount of longitudinal reinforcement was higher than that predicted by the codes of practice. No limitation was necessary up to an amount of about 5%.

- The influence of the a/d ratio, or the M/V relationship, was studied. The AASHTO LRFD shear procedure duplicated the behaviour observed in the Artificial Neural Network results.

7.1.3 Conclusions based on the proposed shear design procedures

Members without web reinforcement

- A general shear design procedure was derived directly from the Artificial Neural Network results taking into account an expression of the size effect originally derived by Fujita et al. (2002). The average V_{test}/V_{pred} ratio for the entire database was 1.13, with a coefficient of variation of 15.46%. This contrasted with the shear strengths predicted by the EHE or ACI 11-3 (EH-91) procedures, whose averages were 1.23 and 1.29, and whose coefficients of variation 23.61% and 31.21% respectively. The proposed method correlated both normal-strength and high-strength concrete beams with a very similar accuracy.

- A simplified shear design procedure was derived from the general procedure by simplifying the size effect term. The average V_{test}/V_{pred} ratio for the entire database was 1.12, and the coefficient of variation 16.10%. Because of its simplicity, it is recommended using this shear design method as a general procedure to obtain the shear strength of normal-strength and high-strength concrete beams without web reinforcement.

- Both methods take into account that the size effect is related to the maximum vertical spacing between layers of longitudinal reinforcement rather than the overall member depth.

Members with web reinforcement

- The general shear design method proposed in Chapter 6 suitably correlated the empirical results, with an average V_{test}/V_{pred} ratio of 1.11 and a coefficient of variation of 18.77%. This contrasted with the shear strengths predicted by the EHE or Eurocode 2 procedures, whose averages were 1.64 and 1.83, and coefficients of variation 26.26% and 40.29% respectively.

- The general shear design method took into account the interaction between bending moment and shear, and therefore, the failure shear strength was dependent upon the bending moment of each given section and not only the geometrical and reinforcing properties of that section. A simplified shear design method and a simplified shear verification method were proposed for obtaining conservatives result independent of the bending moment.

- The simplified shear design method considered the designing shear force V_d to be an input, while the verification method considered V_d to be an output. The V_{test}/V_{pred} ratio was 1.17 and 1.18 respectively for the two methods, with coefficients of variation of 19.56% and 18.71%.

7.2 Recommendations for future studies

The response of prestressed high-strength and normal-strength concrete beams with and without shear reinforcement failing in shear should be studied in a manner similar to that we used to examine reinforced concrete beams in this thesis. A study of the performance of the different codes' approaches, comparing them with test results in the existing literature has already been initiated along with the development of Artificial Neural Networks designed to carry out parametrical analyses in order to study the influence of the prestressing force and the prestressing steel area on different series of beams. The author aims to adjust the proposed procedures for their application to prestressed concrete beams.

Another line of further research would be an experimental study on walls and slabs failing in shear. The expressions given in this thesis are derived from test results obtained from beams, and therefore, the direct use of these equations for designing slabs is not justified. The presence of reinforcement in two directions could improve the response of slabs and walls without shear reinforcement.

Last, but not least important, the author does not know of any existing model able to predict the empirically observed behaviour of deep beams in which there is a reduction in the failure shear stress when the concrete compressive strength is increased. Fracture Mechanics would most likely to be the correct field to address the study of such beams in order to better understand this effect.