

## Structural Concrete: Shortcomings of Current Design and Proposed Revision

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### Current Design

#### Philosophy

Current codes of practice for the design of structures have been developed within the context of the limit-state philosophy [1] (American Concrete Institute 2011, Eurocode 2 2004): A structure or member is first designed so as to exhibit specified performance after attaining its load-carrying capacity, i.e., when its ultimate limit state is reached; the design is complemented or even revised during a process of checking whether the structure or member exhibits the desired behavioural characteristics under service conditions, i.e., at the serviceability limit state.

#### Anticipated benefits

The adoption of the limit-state philosophy as the basis of current codes of practice for the design of concrete structures expresses the conviction that this philosophy is capable of leading to safer and more economical design solutions. After all, designing a structural concrete member to its ultimate limit state requires the assessment of the load-carrying capacity of the member and this provides a clearer indication of the margin of safety against collapse. At the same time, the high internal stresses which develop at the ultimate limit state result in a reduction of the member cross-section and the amount of reinforcement required to sustain internal actions. (Admittedly, the latter economy and, of course, safety itself are dependent on the actual safety factor adopted; nevertheless, the more accurate estimate of the true failure load provides an opportunity to reduce the uncertainties reflected in the factor of safety in comparison with, say, elastic design solutions).

#### Shortcomings

In recent years there has been a relatively small, but worrying, increase in the number of incidents whereby RC structures unexpectedly suffered a brittle type of localised failure that led, in some cases, to collapse [2]. Earthquakes are by far the most usual causes of structural failure, since they often lead to overloading. Although there has been a number of earthquakes that caused extensive destruction in recent years, the collapse of, and severe unexpected types of damage suffered by RC structures at Northridge (California) (Figure 1) and Kobe (Japan) [3] (Figure 2) cannot be attributed to defective work or non-compliance with code provisions. Significant damage not predicted by current design methods has also been suffered by RC structures during the earthquake that hit Athens in 1999 [4] (Figure 3). Vertical structural members suffered damage in the form of criss-crossing diagonal cracking at mid height and not, as predicted by current code design methods, in the end regions of the structural elements. Similar types of failure have also been reported for collapsed columns and piers in Kobe. Therefore, it is not surprising that, in his award-winning article [5], Professor Priestley devotes a section to what he rightly describes as “myth(s)”. Significantly, he states: “Design of reinforced concrete is so full of myths, fallacies, and contradictions that it is hard to know where to begin in an examination of current design.”

However, more worrying than the failures in cases of overload are those which have occurred during construction or under service conditions. A typical case of the former is the totally destroyed during the sinking operation \$180 million Sleipner offshore platform which illustrates how codes may fail to provide accurate predictions of collapse load and/or failure mode [6]. As regards the latter, whatever the actual causes which led to the subsequent sudden collapse of part of the Pipers Row car park in Wolverhampton, the available photograph



Figure 1: Bridge collapse in Northridge.



Figure 2: Pier collapse in Kobe.

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and the accompanying caption “Midland’s slab punches out warning” are not incompatible with this type of failure [7] . More worryingly, a number of punching collapses have subsequently been reported in Canada [8] (Figure 4).

An attempt to remove from design practice some of the myths, fallacies and contradictions referred to by Professor Priestley has been the subject of extensive research work over the last 30 years. Although such work resulted in the development of a finite-element model that proved suitable for both the analysis and the design of concrete structures [9,10] the need still remains for new, simple design methods capable of providing an insight into the physical aspects of concrete behaviour, while, at the same time, achieving the fundamental aims of structural design for safety and efficiency.

### Need for Revision of Design Methods

An extensive investigation into the causes of the code methods shortcomings led to the conclusion that the shortcomings are due to the inadequacy of the theoretical basis of the design methods which are used to implement the limit-state philosophy in practical design, rather than the unrealistic nature of the aims of the design philosophy as such. In fact, it was repeatedly shown that the fundamental assumptions

of the design methods which describe the behaviour of concrete at both the material and the structure levels were adopted as a result of misinterpretation of the available experimental information and/or use of concepts which, while working well for other materials (e.g. steel) or regimes (e.g. elastic behaviour), are not necessarily always suitable to concrete structures under ultimate-load conditions, i.e., at the ultimate limit state [11]. Therefore, it became clear that the theoretical basis of current design methods requires an extensive revision if the methods were to consistently yield realistic predictions as a result of a rational and unified approach.

### Proposed Revision

Such a revision has been the subject of comprehensive research work which led to a new, improved design approach for the implementation of the limit-state philosophy into the practical design of concrete structures [12]. This involves, on the one hand, the identification of the regions of a structural member or structure at its ultimate limit state through which the external load is transmitted from its point of application to the supports, and, on the other hand, the strengthening of these regions so as to impart to the member or structure desired values of load-carrying capacity and ductility. As most of the above regions enclose the trajectories of internal compressive actions, the new methodology has been termed the ‘compressive-force path’ (CFP) method. In contrast to the methods implemented in current codes of practice, the proposed methodology has been found fully compatible with the behaviour of concrete (as described by valid experimental information) at both the material and the structure levels capable of producing design solutions that have been found to satisfy the code performance requirements in all cases investigated to date [12] .

It may also be of interest to note that, although the CFP method might appear, at first sight, to be a rather unorthodox way of designing structural concrete, it is easy, with hindsight, to see that it conforms largely to the classical design of masonry structures by Greek and Roman engineers. These tended to rely greatly on arch action – later expressed (and extended) through the Byzantine dome and the Gothic vaulting. Now, such a mechanism of load transfer may seem largely irrelevant for a beam exhibiting an elastic response. However, for a cracked reinforced concrete girder close to failure the parallel with an arch-and-tie system reveals striking similarities between the time-honoured concept of a compressive arch and the newly-proposed CFP method [12,13].

The CFP method was implemented in design through the development of failure criteria expressed by simple equations which were derived from first principles without the need of calibration with experimental data on structural concrete behaviour. The incorporation of these criteria into the CFP method not only simplified the assessment of the strength characteristics of structural concrete, but also extended its use to the whole range of practical cases covered by current codes of practice for the design of RC structures, earthquake-resistant RC structures included. The verification of the method has been based on comparisons between assessed and experimentally-established behaviour; the results of such comparisons have been confirmed by more recent work [14] which also revealed that designing in accordance with the CFP method widens the range of application of structural concrete [15].

### Concluding Remark

In view of the above, it is considered that time has come for a reappraisal of code provisions which is not confined to merely re-



Figure 3: Column failure in Athens.



Figure 4: Car park punching.

calibrating empirical formulae, but to assessing the validity of the concepts underlying these formulae.

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