# Impact of rational approaches on design practice

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# Impact of Rational Approaches on Design Practice

## Impact d'une approche rationnelle sur la conception des ouvrages

## Einwirkung einer rationalen Betrachtungsweise auf die Entwurfspraxis

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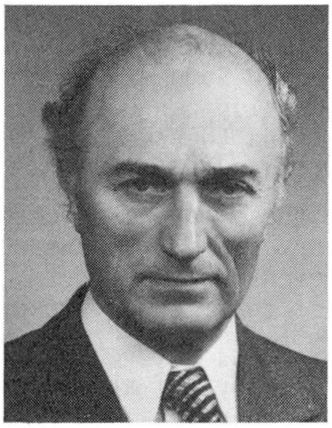

Daniël Vandepitte, born in 1922, designed a number of bridges at the onset of the prestressed concrete era. He later taught and wrote a three volume book on structural analysis. He acted as a technical consultant, mainly to an agency assessing the safety of civil engineering and buildings structures.

**SUMMARY**

A few examples of the potential impact of a rational design approach for structural concrete on design practice are discussed, and it is attempted to learn a lesson from rather arbitrary constraints on past design practice. The following topics are commented upon: unreinforced concrete, structural concrete reinforced with only steel fibres, the merits of limited prestressing, external prestressing, mechanical modelling, prestressed concrete suspension bridges, the concept of the prestressed concrete suspension bridge with a triangular system of suspenders, and reliance on the tensile strength of concrete.

**RÉSUMÉ**

L'impact potentiel d'une approche rationnelle du béton structurel sur la pratique de la conception et du calcul des ouvrages d'art et des bâtiments est illustré par quelques exemples. L'auteur essaie, en outre, de tirer une leçon de restrictions plutôt arbitraires qui entravaient les projeteurs par le passé. Les sujets discutés sont les suivants: le béton non armé, le béton structurel armé seulement de fibres d'acier, les mérites de la précontrainte restreinte, la précontrainte extérieure, le modelage mécanique, les ponts suspendus en béton précontraint, le concept du pont suspendu à tablier en béton précontraint et à système triangulaire de suspentes, et la prise en compte de la résistance du béton à la traction.

**ZUSAMMENFASSUNG**

Einige Beispiele der möglichen Auswirkung einer rationalen Betrachtungsweise auf die Entwurfspraxis werden besprochen, und es wird zugleich versucht, eine Lehre aus früheren willkürlichen Einschränkungen zu ziehen. Die folgenden Themen kommen zur Sprache: unarmierter Beton, nur mit Stahlfasern armierter Konstruktionsbeton, beschränkt vorgespannter Beton, externe Vorspannung, mechanische Modellierung, vorgespannte Hängebrücken, das Konzept der vorgespannten Hängebrücke mit dreieckigem Hängersystem und Nutzung der Betonzugfestigkeit.

## 1. PRELIMINARY REMARKS

1.1 The writer of the present paper does not possess a reliable crystal ball and therefore does not purport to venture any predictions about prospective developments, but will pursue the less ambitious goal of discussing a few examples of more or less unrelated areas where a rational design approach for structural concrete may affect design practice in the future, while trying to learn a lesson from the vicissitudes of past design practice.

1.2 Codes, whether they are legally binding or not, exert a powerful influence on design practice, more so than research reports or symposium proceedings, although part of the content of these may eventually trickle into codes. Engineers who have been active as members of code writing committees know that a new code is generally copied to some extent from a previous edition. Once in a long while a given recommendation can be traced back to a 50 year old predecessor of the code and is found to have been reproduced, possibly verbatim, in a number of successive editions.

The committees which wrote these may have acted wisely in borrowing from older standards. They may know or assume that there were excellent reasons for introducing a particular requirement in the first place. Their decision to retain it may be justified by the fact that it has stood the test of time.

However, it is quite likely that, after a few decades, hardly anybody is aware of the original rationale, if any, of an old recommendation, and, if a number is involved, of the reason why a particular figure has been selected. Many codes were initially written to meet an urgent need and were therefore of limited scope. Re-editing them, essentially unchanged, accounts to some extent for the incompatibility of certain features of codes covering adjacent fields. It is necessary to reassess from time to time the arguments underlying known rules, to delete them or to place them on a more rational footing, if no credible justification can be found. The Colloquium on Structural Concrete sets out to do that systematically and that purpose is entirely commendable.

It should be emphasized, however, that even recommendations regarding structural concrete which are not at variance with any other recommendations regarding structural concrete should not be taken for granted.

1.3 Once in a while, one encounters the notion that a type of structure is not permissible if it is not allowed and codified explicitly in existing standards. That is a deplorable attitude because it stifles innovation.

## 2. UNREINFORCED CONCRETE

The Final Invitation to the Colloquium on Structural Concrete states that structural concrete represents a continuous spectrum from unreinforced concrete to the most involved combinations of concrete with steel reinforcement. Implicit in this definition is the assumption that present codes allow the use of unreinforced concrete. But do they really ?

If unreinforced concrete should be acceptable at all, it would seem to be in structural elements that are subjected almost exclusively to compression by the external loads, i.e. in columns and walls. Yet, the First Draft of the CEB-FIP Model Code 1990 specifies a minimum longitudinal reinforcement of 0,8 % in columns [2, p. 10-5] and a minimum vertical reinforcement of 0,4 % and a minimum horizontal reinforcement of 0,12 % in walls [2, p. 10-6] . It is stated, moreover, that these minimum measures constitute obligatory prerequisites of the application of the Code [1, p. 4-2] . The CEB-FIP Model Code 1978 prescribes the same minimal reinforcement [3, p. 189-191] , except that the requirement for horizontal reinforcement in "reinforced concrete walls" is at least 50 % (instead of 30 %) of the vertical reinforcement. The wording of the article regarding precast wall panels in the draft of the 1990 Model Code [2, p.14-9] does imply, however, that unreinforced walls are permissible, provided that they are precast.

Of course, one can easily imagine reasons why a certain amount of steel in concrete columns and walls is beneficial. For one thing, it hampers cracking and the propagation of damage. For another, it serves the purpose of resisting bending induced in the vertical structural elements by beams connected monolithically with the columns and by slabs connected monolithically with the walls. Reinforcing steel also renders structural elements carrying vertical loads less vulnerable to accidental lateral loading, due, for example, to a horizontal bump against the column or wall or to an explosion. But one may well wonder whether and why exactly reinforcement is really necessary, especially in concrete walls, since concrete has been depicted in recent years as a fairly ductile material.

The minimum percentages, 0,8 % and 0,4 % and 0,12 % , do not appear exorbitant, but they may amount to a lot of steel in walls. Is there a rational basis for these particular figures ?

Asking these questions seems legitimate in view of the existence, in Switzerland and probably elsewhere, of 20 storey buildings whose brick masonry walls are load bearing and do not contain steel or reinforced concrete frames. Those masonry walls are not reinforced. Yet the tensile strength of brick masonry, especially that of its horizontal joints, is definitely lower than that of concrete, and reinforced concrete floor slabs framing into a masonry wall also generate bending.

Do concrete walls subjected to little or no bending and transverse shear need to be reinforced, while masonry walls do not ? Are designers of concrete walls too timid or are designers of masonry walls reckless ?

If a detached examination of these questions led to the conclusion that the designers of tall buildings with load carrying brick masonry walls have not been remiss, that outcome might stimulate the erection of buildings having considerably more than 20 storeys and unreinforced concrete bearing walls.

The "Introduction to the CEB-FIP/MC 90" [1, p. VI] announces the eventual addition of a chapter concerning plain concrete. The wording "plain concrete (such as, for example, mass concrete)" suggests that the chapter will not focus on unreinforced concrete bearing walls, although it may not exclude them.

## 3. STRUCTURAL CONCRETE REINFORCED ONLY WITH STEEL FIBRES

Promoters of steel fibre reinforced concrete would like to reinforce structural concrete beams and slabs (not resting directly on ground) and tension piles with steel fibres only. One may doubt the economic merit of such structural elements because their fibre reinforcement is located partly in regions where no tensile stresses exist, and in the regions where reinforcement is needed, many fibres are so orientated that they are inefficient.

However, the said promoters are not given the chance to prove that the doubters are wrong, because such applications are prohibited by codes of practice [4] . The ban is based on the possibility that the distribution of the fibres in the concrete may be non uniform and that critical regions may contain too few fibres. The proscription should be lifted if and when mixing methods are developed which ensure uniform dispersion of the fibres and a practical way to ascertain uniformity of dispersion is available.

## 4. FULL PRESTRESS VERSUS LIMITED PRESTRESS

At the time of the inception of prestressed concrete technology, 50 years ago, full prestress was generally considered as technically ideal. This was partly due to the then dominant view that reinforced concrete and prestressed concrete are fundamentally different materials. Many prestressed concrete beams manufactured in those days had little passive reinforcement or none at all.

Reference [5] describes tests on two prestressed concrete beams of 28,8 m span. They contained neither passive longitudinal reinforcement, nor stirrups. Except for a few unstressed rebars in the end blocks, they were reinforced only with post-tensioned 7mm wires. The beams were taken from a dismantled 30 year old bridge (it would not be easy to find recent beams of such large size and almost totally devoid of passive reinforcement). The girders exhibited a small number of wide cracks under increasing load. They deflected considerably before they failed, and in that sense they were certainly not brittle. Whether they were tough in the sense that a very gradual decrease in their loading would have accompanied still increasing deflection after the load had reached its ultimate value, is unlikely, but could not be ascertained because the tests were not deformation controlled. It is probable that few deformation controlled tests to failure have been carried out on large prestressed concrete beams containing virtually no passive reinforcement. Anyhow, the two beams discussed here collapsed suddenly and explosively by disintegrating into a fairly small number of large pieces of concrete, not by crushing of the compressed flange.
That is a reason for believing that it is in many cases technically better to withstand the tensile forces in structural elements subjected to bending and to shear partially with active reinforcement and partially with passive reinforcement, rather than with active reinforcement alone. Limited prestressing has other well-known mainly economical advantages : less prestressing steel (partially offset by more passive rebars), less room needed in the cross-section for prestressing tendons and ducts, a smaller prestressing force in the precompressed concrete flange and therefore a flange of smaller size, less creep deformation. The reverse side of the coin : the increased importance of the effects of fatigue (which, in the case of railway bridges, may justify the requirement : no tensile stresses in the concrete under maximum service loading), and the increased risk of cracking.

It is highly laudable to strive, as the Colloquium on Structural Concrete does, for methods of design and analysis that allow for a consistent and continuous spectrum of designs corresponding to a wide interval of degrees of prestress. That is quite the opposite of dogmatically denouncing limited prestressing, as one school of thought was prone to do in the past. In the writer's opinion, engineers should, in the future, resort more often to limited prestressing of beams and, in many cases, will thus design structures which are better, technically and economically.

## 5. EXTERNAL PRESTRESSING

External prestressing has been used in many structures for more than 45 years, practically from the onset of prestressing technology. Prestressing cables may be placed on either side of the web of a concrete plate girder or inside a box girder. References [6, p. 108 and 190] , [7], [8] and [9, p.6 and 313] are just four among numerous, decades old publications describing structures with external prestressing. There have been mishaps, due to sloppy grouting of the prestressing tendons and to their subsequent corrosion. For that matter, internal tendons have been known to sustain corrosion too. There are, on the other hand, structures with external prestressing that are decades old and in excellent shape.

There were no grounds for rejecting external prestressing on principle. Yet, the concept used to be opposed in some quarters. The 1978 CEB-FIP Model Code [3, p. 63] mentioned it, but otherwise ignored it. External prestressing has been rediscovered in the last few years and advocated in a flurry of fairly recent papers which quite rightly emphasize the considerable advantages that it has had all along. The technology described in those papers hardly differs from practice as it had evolved in previous decades. The essential requirement for durability was and remains care in protecting the prestressing tendons from corrosion.

To be sure, in some cases there may be (almost) no bond between external tendons and the concrete, and the corrolaries of that situation should be allowed for in the analysis. The effects of the prestressing force, considered as artificially created external loads [10] and including both a longitudinal compressive load and transverse loads in sections where tendons change direction, decrease gradually as a result of shrinkage, creep and relaxation, but they may increase under live load because the tendons are forced to deflect together with the concrete beam. Bond is seldom lacking completely, though, since the friction generated where the slope of the tendons changes is similar to bond. Furthermore, it is often possible to achieve a more rigid longitudinal connection at such points, if so desired, and the prestressing force then varies discontinuously from one part of the tendons between two successive points of deviation to an adjacent part.

Provided that those features of external prestressing are taken into account in the analysis and construction, it is and always has been just as sound a prestressing method as prestressing with internal bonded tendons. The satisfying circumstance that external prestressing is now recognized in the draft of the 1990 CEB-FIP Model Code [1, p. 1-9] enhances the concordance between the code and the facts, and it should encourage designers of concrete structures to take greater advantage of the substantial benefits of that prestressing mode in the future.

## 6. MECHANICAL MODELLING

The introduction and the acceptance of strut-and-tie models and of B regions and D regions [2, p. 6-1 and 6-16] [11] [12] represent an important progress, even if implementing these concepts may still require much thought and discussion. For example, allowing an angle as low as arc cot 3 = 18,4° between the imaginary compression diagonals in the web and the chords of a beam subjected to shear [2, p. 6-17] does seem somewhat excessive and its safety should be checked before it is allowed to stand. The strut-and-tie model has great merits :

- It goes back to basics, the lower bound theorem of plasticity theory, and even much further back, to a fundamental principle of statics, the theorem of the triangle of forces enunciated in 1586 by the Flemish engineer and scientist Simon Stevin [13, p. 90].
- It provides insight into the interplay of forces within a structure.
- It is very versatile and enables an engineer exercising his intuition wisely to devise sagacious solutions, even in cases of unusual structural arrangements, which are hardly amenable to treatment by a cut-and-dried method of analysis.

Strut-and-tie models and the concept of B regions and D regions supply designers with powerful design tools.

## 7. PRESTRESSED CONCRETE SUSPENSION BRIDGES

The first self-anchored suspension bridge whose concrete stiffening girders are prestressed by the main suspension cables was built in 1954 [14]. Figure 1 is an outline of the structural system, reduced to its bare essentials and drawn without the towers, with far too few suspenders and with an exaggerated camber of the stiffening girder. At the time, different design rules applied to reinforced concrete and to prestressed concrete in Belgium. But is the suspended structure reinforced or is it prestressed ? Both views can be argued :

- The stiffening beams do contain a fair amount of passive reinforcement, but there are no prestressing tendons within the depth of the suspended structure. Consequently, it is reinforced concrete.
- Although the prestressing cables are located above, even far above, the concrete floor system, the latter is prestressed by them. Hence it is prestressed concrete.

Incidentally, "prestressed concrete", taken at face value, is a widely applicable general phrase : a concrete arch, for example, is prestressed by its own weight. So is a masonry arch.

What is depicted in figure 1 is an obvious example of a structural system which may be analysed efficiently by conceiving of the prestressing effects as external loads acting upon the concrete component and all proportional (except for second order effects) to the horizontal component of the tensile force in the main suspension cables. The prestressing effects are (fig. 2) : the compressive forces acting upon both ends of the stiffening girder and the forces exerted upwards by the suspenders upon the girder (and including the effect of the camber if a perfectly straight beam is substituted for the actual cambered beam, as has been done in figure 2).

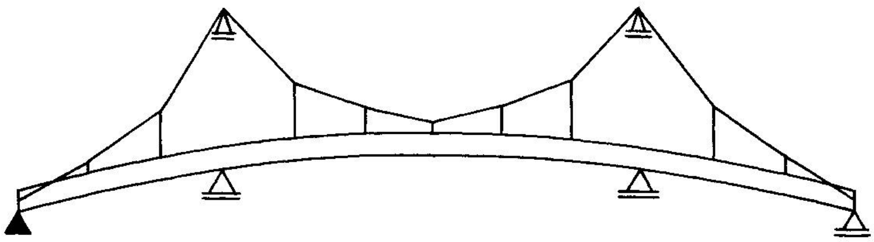

Fig. 1 - Outline of a prestressed concrete suspension bridge

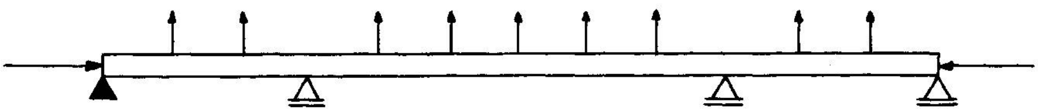

Fig. 2 - Prestressing effects on the stiffening girder of a prestressed concrete suspension bridge

The analysis of the bridge and of similar bridges was based on the simple and transparent model in figure 2. The analysis is expounded in some detail in reference [15]. As in other prestressed structures, the prestressing effects decrease as time elapses. The system could be so designed that the upward forces acting on the floor structure balance the permanent loads at a certain stage, for example immediately after the prestressing operation. A more efficient design requires, not amazingly, that the upward forces exceed the permanent loads, even after the upward forces have decreased as a result of the gradual loss of prestress.

The combinations of factored loads, which the bridge should be able to withstand before reaching an ultimate limit state, should be the usual combinations and should include i.a. the dead load multiplied by the usual corresponding partial safety factor, say 1,35. Thus, the dead load multiplied by 0,35 and other factored loads should be superimposed on the situation comprising the dead load itself and the (factored) prestressing forces. If, instead of that, the designer applied the factor 1,35 to the sectional forces existing in the cables and in the stiffening girders after the prestressing operation, he would not, the writer believes, be complying with the general spirit of the concept of partial safety factors, since he would fail to take account of the way in which the interaction between the components of the structural system influences the sectional forces in those components at loading stages exceeding the service loads.

## 8. CONCEPT OF THE PRESTRESSED CONCRETE SUSPENSION BRIDGE WITH A TRIANGULAR SYSTEM OF SUSPENDERS [16]

The main difference between the type of bridge discussed in section 7 and the bridge system outlined in figure 3 lies in the fact that the latter has slanting instead of vertical suspenders. The suspension bridge is self-anchored in both cases and consequently it does not need two external anchorages capable of resisting large horizontal forces. If, given the live load intensity, the spans of the bridge sketched schematically in figure 3 are long enough, the dead load produces so much tension in the inclined suspenders that it is never exceeded by compressive stresses superimposed on it later and generated by the live load. Therefore, the suspenders are never called upon to withstand compression and they may be designed as cables or ropes.

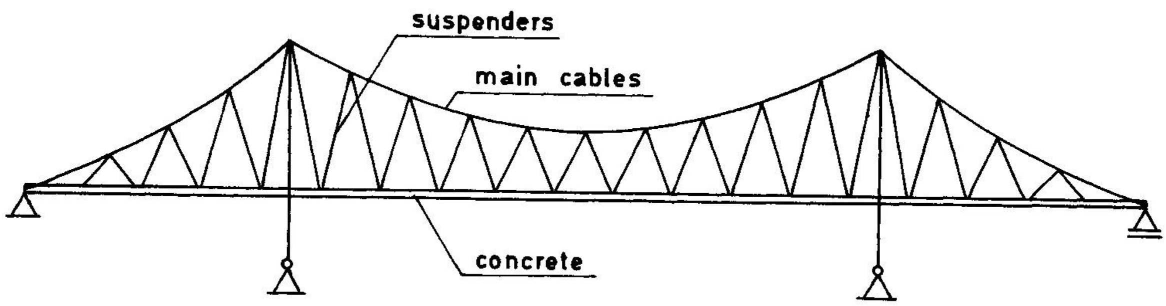


Fig. 3 - Outline of a prestressed concrete suspension bridge with a triangular system of suspenders

Under live load the truss action in the structural system as a whole is so dominant that the suspended concrete floor structure is subject to little longitudinal bending, definitely less than the bending induced in the stiffening girders of the type of bridge schematized in figure 1. In figure 3, the stiffening function is assigned to the truss, thereby obviating the necessity for the deck to possess any flexural rigidity of its own in excess of the rigidity it needs to resist local bending and buckling in between suspenders. As a result, the floor structure may be quite slender. Moreover, it is prestressed longitudinally by the horizontal component of the forces applied to its ends by the main cables, so that what little longitudinal bending arises from the loads does not require very much passive reinforcement. For all these reasons, the structural system described seems quite economical and attractive (see also 8.1 Note).

However, dimensioning the passive (or active) reinforcement within the suspended concrete deck would not be a straightforward process, if some of the customary design methods were to be utilized. Horizontal prestressing is applied predominantly by external forces at both ends of the bridge and only to a minor degree at the suspension points, where it originates from the slanting suspenders as an outcome of the live load. As in the case of the bridges discussed in section 7, the prestressing cables are the main suspension cables and they are located far outside the depth of the bridge floor. An approach which does not draw a fundamental distinction between reinforced concrete and prestressed concrete, but treats both as variants of the same material, structural concrete, furnishes clear answers to the design questions raised by the types of structure discussed in sections 7 and 8.

8.1 Note

Of course, the structural system, as it is portrayed in figure 3, is able to carry itself only after it is completed. If the topography of the site is such that elevated bridge ramps are necessary, a construction procedure can be devised in which no scaffolding under the bridge floor is involved. In the case of figure 4, the main suspension cables can be temporarily fastened in C and D to two large concrete slabs which are cast simply on the ground on either side of the river and which resist sliding by friction developed by the weight of the earthen embankments placed on top of the slabs. Precast portions of the bridge floor are then suspended from the cables (the corresponding deflection of the cables is omitted from the sketch).

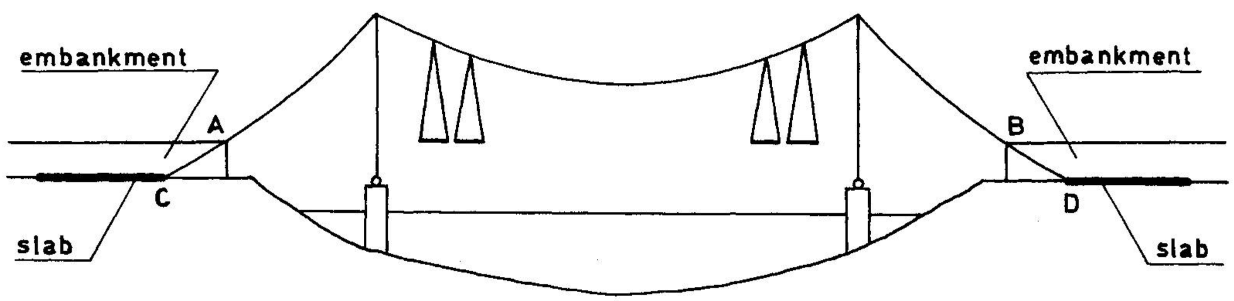


Fig. 4 - Construction procedure

When all the segments of the floor structure are erected, they are made continuous, the tensile forces in the cables are transferred to the suspended deck at A and B , and the parts AC and BD of the cables are deactivated.

9. RELIANCE ON CONCRETE TENSILE STRENGTH

Code writers, teachers and designers have often felt uneasy when confronted with and reflecting upon the inconsistency between the stated general design assumption that concrete does not resist tensile stresses and the realization that, in fact, we often rely and are forced to rely upon concrete tensile strength, mostly well-nigh unwittingly, but quite systematically when shear in slabs comes up. In recent years admirable efforts have been made towards a better understanding of tensile behaviour, tensile strength, strain softening and fracture energy of concrete [17] [18]. It is to be hoped that these efforts will generally improve the coherence of structural concrete strength theories and, more specifically, that they will lead eventually to a scientifically based treatment of punching shear, a problem that has never been solved in a really satisfactory manner.

The effects of such a development could be far-reaching. To mention just two examples :

- It is conceivable that better insight into the reliability of concrete tensile strength may enable the rule "Linear members of minor importance such as lintels ... , may be designed without web reinforcement" [2, p. 6-16] to be made applicable to more important linear members.
- Designers of flat slabs, in order to take care of punching shear around columns, often resort to more or less elaborate devices obtained by welding rolled steel sections and embedded in the concrete slab. A more coherent and efficient use of concrete tensile strength, resulting in a more constant safety factor, may diminish the need of sources of strength other than the own strength of the concrete and of rebars.

## 10. CONCLUSIONS

A comprehensive consistent approach to structural concrete design and analysis, valid without descrepancy for the whole spectrum between unreinforced concrete and reinforced and/or prestressed concrete with a wide range of degrees of prestress, is a boon to designers. It eliminates ambiguities and confusion. It enables engineers to find reliable solutions for unusual problems, such as those arising in connection with innovative structural concepts.

It is salutary to question the rationality of received rules and ideas from time to time, for example those regarding the minimum reinforcement in concrete walls and columns.

Engineers who have the creativity and daring needed to go off the beaten track should not be obstructed by dogmatic prohibitions. Codes should not ban any structural concepts or arrangements, unless there is a good reason, based on more than preconceived ideas, to cast serious doubts on their soundness.

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