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The Need for Consistent and Translucent Models

Nécessité de modèles cohérents et intelligibles

Warum wir einheitliche und verständliche Modelle brauchen

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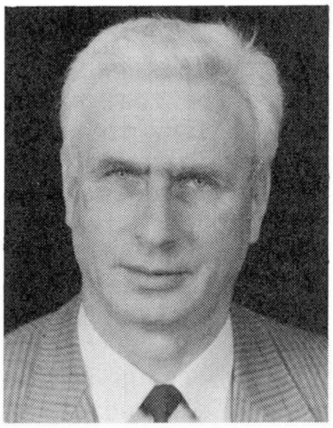

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SUMMARY

Only through an intelligent model can a complex reality became translucent and understandable to a designer and there lies the key to quality in structural engineering. It must be the aim of this colloquium to agree on a modelling philosophy which covers consistently the whole range of structural concrete. The individual designer must acquire the art of finding the right model to suit each case, neither too special nor too general.

RÉSUMÉ

Une réalité complexe ne peut être comprise qu'à travers un modèle cohérent et intelligible; pour l'ingénieur ceci est la clef d'un dimensionnement efficace particulièrement dans le domaine des structures. Le but du Colloque est de mettre en évidence le sens de cette démarche, afin qu'elle concerne directement tout l'ensemble des structures en béton. Pour l'ingénieur projeteur, il s'agit d'apprendre dans chaque cas à appliquer le modèle, qui à juste titre, ne se doit de décrire la réalité ni d'une façon trop détaillée ni trop simplifiée.

ZUSAMMENFASSUNG

Weil man nur bearbeiten kann, was man versteht, ist die Wahl eines intelligenten Modells, das ein komplexes Tragwerk durchsichtig und verständlich macht, der Schlüssel zur Qualität im Konstruktiven Ingenieurbau. Im Rahmen dieses Kolloquiums sollen vor allem die Modelle diskutiert werden, die die ganze Breite des Konstruktionsbetons einheitlich beschreiben. Der entwerfende Ingenieur muss lernen, im Einzelfall das richtige Modell zu entwickeln, das die Wirklichkeit weder unnötig fein, noch zu grob vereinfacht beschreibt.

1. THE NEED FOR CONSISTENT AND TRANSLUCENT MODELS

The appeal of structural engineering is, that it combines rationality with creativity. The structural engineer, as does the crafts-man, forms material such that it serves its purpose,
i.e. - fulfills its function (utility)
- during an expected lifetime (durability)
- at a reasonable prize (economy)
- with a pleasing form (beauty)

and today we are inclined to add
- respectful of natural resources (harmony).

Obviously forming a material to this end can be successful only if one really knows and understands it. Since the real nature of all our materials, especially that of structural concrete, is very intricate and puzzling and therefore even more so whole structures made from such material and exposed to a natural environment, the structural engineer needs models as a medium between his capabilities and reality. Without such models of abstraction and simplification he would be completely subject to trial and error, a method which is especially worthless in structural engineering where each object is a prototype which has to be invented anew and whose behaviour has to be predicted.

The translation of a reality, which up to then existed only in his mind, into the right models which serve him to predict the utility, durability, economy and beauty of his structure to be build, is one of the main challenges to the structural engineer, a semi-rational intuitive step within the whole planning process, close in quality only to the creative conceptual design. Poor modelling results in poor quality of the structures, vice versa.

Looking at the planning process as a whole it becomes immediately clear, that one model would not help and only translate reality into a black box. Rather several additive models are required.

From that it follows that
- the different models which are to be applied in sequence must be consistent with each other

and that the individual models shall
- neither be too special
- nor too general.

A model and as a consequence to it a method of design or analysis, which is too special will not permit transferability and generalisation. If it serves only in points it will not augment or even multiply the experience of its user and therefore not deserve the attribute to be a practical or design model. Too spezialized models cannot be consistent amongst each other. Consistency and specialisation are contradictions in themselves.

It cannot be a design model. In certain cases however and thanks to the efficiency of modern computers such black box models (and analysis or programs associated with them) through parameter variation and sensitivity studies may on a research level be very useful and such deserve the attribute of a research model.

The art of finding the right model and applying the right method of analysis consists in defining and asking for "just enough" and not in "as much as possible". Any redundant refinement is destructive as is any substantial ommission. There are certain data, which the designer will quite happily do without. False accuracy distracts the mind. The time wasted for it will be found wanting for the design task.

2. RESEARCH MODELS, DESIGN MODELS, EXPERIMENTS

Following the above and also earlier writing of Duddeck /1/ on this subject and in view of the ongoing sophistication of modelling techniques with structural concrete it appears useful from an engineer's point of view to differentiate between

- research models and
- design models.

The research model tries to be as close as possible to reality and tries to find an explanation for a phenomena. Therefore it will use real loads, the latest constitutive laws, sophisticated Finite Elements etc. If a test is available, analytical and experimental results must agree.

The design model will reduce reality to its most significant parameters, will idealize loads, the statical system, the safety concept etc. The only criteria is that the structure designed on this basis is clearly understood and, when built, behaves satisfactorily.

This shows, that the research model tries to play and can play a similar role as large scale testing does and that therefore some day experiments may be replaced by sophisticated modelling techniques /2/. The research model may even supply more information as can the experiment - assumed of course, that some day it is really possible to precisely substantiate by way of an analytical model the carefully documented experiment on a structural concrete member.

The experiment inseparably integrates all scattering variables so that strictly speaking it is "only" good for falsifying a theory, impossible of being neatly interpreted without additional theoretical modelling. The theoretical modelling of structural concrete has the character of a theory i.e. that of transferability and universal validity because here every single parameter is individually variable. Therefore we must insist, that the experiment shall never be used as a sole source of information but must be based on design model required anyhow for the design of the test specimen and if necessary further explained by a research model. If this is not observed misinterpretations or at least fruitless disputes are the consequence. In case of structural concrete the most frequent misinterpretation results from the fact, that concrete's tensile strength is there, especially in a well cured and protected test specimen, but that it should be made use of only under very specific conditions which can be incorporated in a design model but not in an experiment or its corresponding research model (see sub-theme 2.5 of this Colloquium).

Experiments as research models describe nature, something which is already there in nature or in a test specimen. They cannot teach us what we should do, but only what we should not do. For the creative design and for innovative thinking we need the aid of a design model.

3. SOME GENERAL REMARKS ON MODELS FOR STRUCTURAL CONCRETE

In order to discuss the different types of models and to understand how they are interrelated, a look at the different steps of the planning process, given in a simplified representation in table I may be helpful.
In the context of this Colloquium on Structural Concrete we may restrict ourselves to the constitutive models describing the material behaviour needed for "Dimensioning" and "Review".

Before doing so it should however be mentioned, that "Detailing" can be omitted here and done based on experience only if it is defined in such a way, that it does not contain any hidden part of dimensioning as it frequently does. Finding the required amount and layout of reinforcement and shaping the concrete down to the smallest detail of a joint or node is called dimensioning. Only respecting rules of spacing or cover etc. whilst doing the working drawings is called detailing and even then it is geometrically interconnected with dimensioning.

Dimensioning (or design) means to fix the dimensions of a member and the amount of reinforcement required to carry a given set of loads over a certain period of time.

Review or validitation or check means to find out the behaviour (deformations, cracking etc.) and amount of load a member is able to carry if all its dimensions and steel is known.

Dimensioning is linked to the conceptual design, a blend of rationality and intuition, where much of the subjective experience of the designer and the objective boundary conditions of a given case merge. The assessment of the dimensions requires simple and transparent models and methods. Therefore dimensioning is the playground of design models. In simple cases, the experienced designer will be satisfied with dimensioning only and proceed from there to the working drawings directly. In more delicate cases dimensioning may assume a more preliminary character and be followed by a refined review or check.
Review similar to experiments - if at all - will always have to follow dimensioning. It should serve no other purpose than to confirm what the designer already knows.
The models or methods applied for review must be at least as or more informative or disclosing as those used for dimensioning if a review should make sense at all. Therefore review is the playground of sophisticated modelling techniques and even research models may be applied there. If in the worst case the designer is not able to carry out such a review himself, by whatever reason, as he would usually also not do a confirming experiment himself, but finds himself confronted with its results, he will have no problem with them, if he really cared for a prediction of these results whilst doing the dimensioning. Thus the designer expects from research models nothing but a confirmation of what he already knows.

To repeat it: Especially in view of the progress in computeroriented analysis we must encourage the designer to do the dimensioning, the pre-diction with intelligent simplified models and methods and to compare them with the results of the "exact" analysis. Where significant disagreement is found, he must look for the cause. The searching and finding is very instructive and serves to train the designer's understanding of structural load behaviour.
With this in mind we can welcome the advancement of computer-oriented modelling techniques because they restore the significance of the simplified design methods by serving as a safety net. Thanks to that the structural engineer may once again revive his inventive talents.

4. THE SPECIFIC MODELS FOR STRUCTURAL CONCRETE

If the above could be agreed upon, then the choice of the specific models should not be a problem at all: As accurate as necessary (not as possible) for the intended use which means that accuracy or density of information may increase if we step down along table 1.

Table 1.
The different steps of the planning process for a concrete structure and the type of models associated with them:

Functional Requirements including social and economical environment	Defined, given
Conceptual design: definition of overall shape and of individual members, choice of materials main details, construction concept.	Experience, intuition simple, mechanical models of subjective character, geometrical models (architectual mock-up).
Loads environmental (climatic impact)	Measurements, idealisation probalistic models
Material laws	constitutive models
Dimensioning Member stiffness	Force-deformation-models
Analysis (sectional or inner forces)	mechanical models (simplified)
fixing of dimensions	safety concept, experience
Detailing	experience, rules
Review Analysis (check of load capacity) if unsafe	mechanical model safety concept (refined)
Beauty check if ugly	architectural model
Working drawings	geometrical model
Specifications and tender documents	model
Submission (economy check) if too expensive Ready for construction	model

With respect to the constitutive models the degree of accuracy should clearly correspond with the particular application i.e. design or research respectively dimensioning or review. It must further be clearly differentiated between a consideration of the overall behaviour of a structure under service condition, when in principle mean values apply, or the search for a local failure, when basically extreme values must be combined. This further shows, that the choice of the appropriate constitutive model is closely related to the safety concept. Since Josef Eibl accepted the invitation of the Scientific Committee to prepare a special report for this Colloquium on this important subject /3/, it will be sufficient to touch the constitutive models in this paper only whilst discussing models for dimensioning and review.

For dimensioning the classical stepwise approach
- choice of a statical system
- definition of member stiffnesses (with respect to the determination of the inner forces only necessary for redundant systems)
- analysis of sectional or inner forces.
- dimensioning remains valid, even, if for simplification inconsistencies are to be accepted.

The most common or classical inconsistency derives from applying as a material model Hooke's law (linear - elastic) for the analysis but modelling the real behaviour of cracked structural concrete whilst dimensioning. However it is not only justified by simplification but because it also gives satisfactory results since a reinforcement layout which is oriented at the linear elastic stress distribution will be right for serviceability and simultaneously concerning safety the lower bound method of the theory of plasticity is satisfied.

For the review, as against that the chances of applying consistent models are much better. Whilst analyzing the inner stresses or the overall load capacity realistic non-linear or idealized elasto-plastic or purely plastic constitutive material models may be used.

This shall be carried out in some more detail for the most common types of structures
- structures made from linear or one-dimensional members such as beams, frames and arches
- two-dimensional plane structures with in-plane loading such as deep beams
- two-dimensional plane structures with transversal loading i.e. slabs
- three-dimensional structures with broken or curved surfaces i.e. folded plates and shells.

It should be stressed, that this conventional way of defining structures is not really helpful and did cause a lot of confusion and useless discussion, at least as far as the separation-line between the first two is concerned. It is in fact not only the global geometry but the local geometry as well and of course the type and distribution of the loads resp. reactions, which governs the load bearing behaviour and thus the approach to it via a mechanical model.

The approach through the subdivision of a structure in its B- and D-regions however is rational, straightforward and simple.

It clearly leads the way towards the appropriate mechanical model(s) and analysis - though of course it is not at all a compulsory or the only possible approach, but obviously the most practical and convenient. So this definition will further be used additionally. [1]

4.1 Models for structures consisting substantially of B-regions e.g. beams, frames and arches

This concerns the majority of the daily building activity (even more if we include the slabs, see sect. 4.3). Though these structures consist widely of B-regions (fig. 1 shows a typical example) they only in very rare cases can do without any D-regions. In fact, because there exist well established methods for dimensioning and review of the B-regions, the majority of problems, poor performance and even failures appear in D-regions. From that point of view the former "shear battle" and ongoing strive for further refinements of the B-region design appears disproportionate.

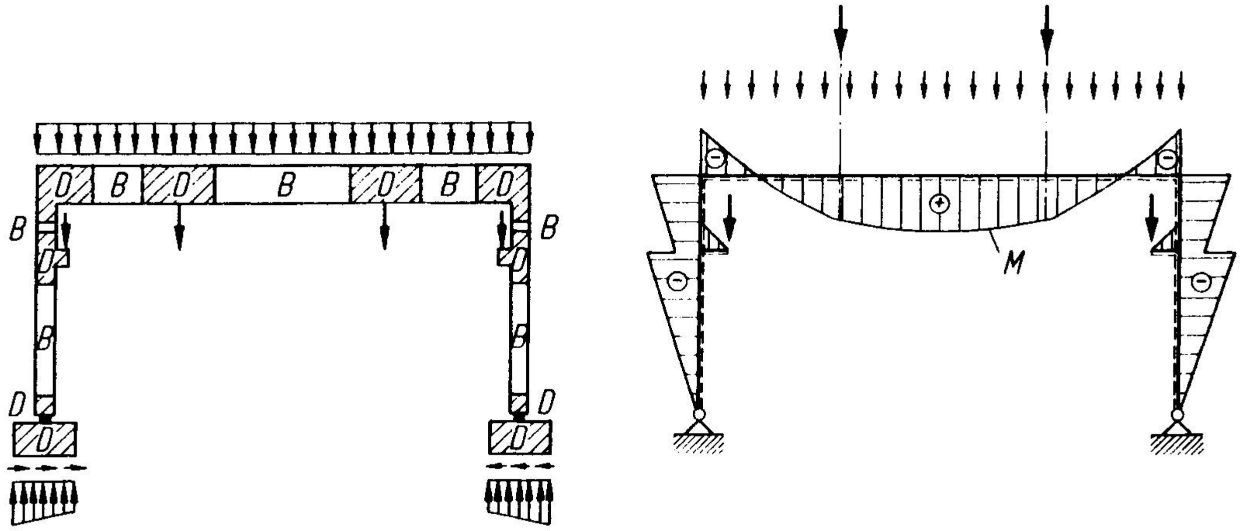

Fig. 1: A frame structure containing a substantial part of B-regions, its statical system and its bending moments.

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1. This method was first introduced in /4/ and further published in /5, 6/ and later referred to by other authors. It shall therefore not be repeated here.

In B-regions the Bernoulli-hypothesis of plain strain distribution is valid (B stands for beam or Bernoulli). Their internal state of stress is easily derived from the sectional forces (bending and torsional moments, shear and axial forces) through clearly defined models as discussed below.

Regions in which the strain distribution already for a linear-elastic stress-strain law is significantly non-linear due to static (e.g. concentrated loads) or geometric (e.g. corners, bends, openings) discontinuities are called D-regions (where D stands for discontinuity, disturbance or detail).

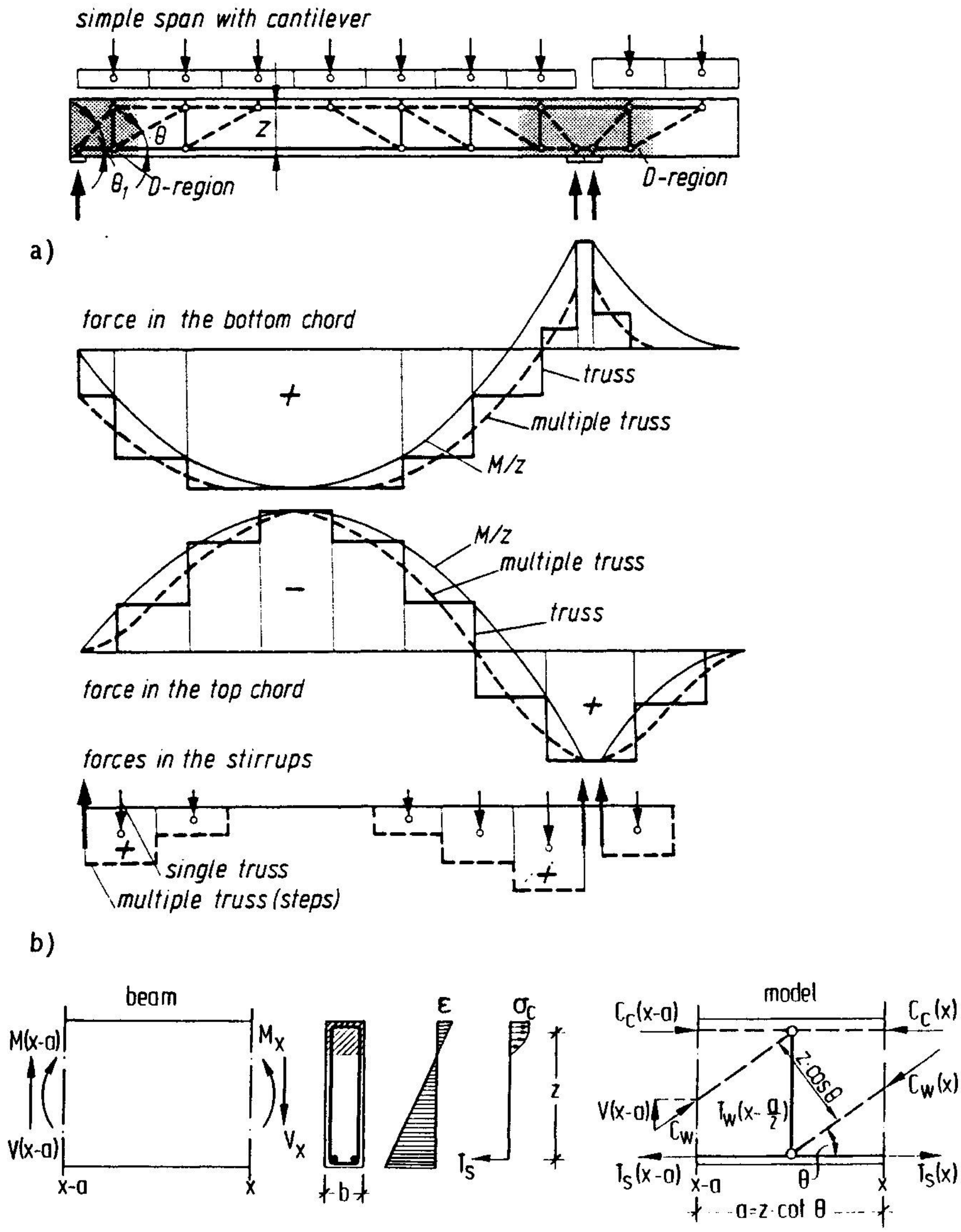
On the other side, even in times of ever increasing computer efficiency, it would be unreasonable to begin immediately to model these structures with strut-and-tie-models (STM) or even with finite elements. Rather the common practice should be maintained to model the real structure by its statical system, i.e. one-dimensional elements following the center lines of the real sections, and to analyse its support reactions and sectional effects, the bending moments (M), normal forces (N) shear forces (V) and torsional moments (T). It should be emphasized, that this analysis in cases of structures with predominantting B-regions such as in fig. 1 yields satisfactory results for the deformations and forces if it is carried through the D-regions even, i.e. if even the D-regions are for that purpose treated as B-regions - but only for this overall analyis, not for the dimensioning of the D-regions themselves! In cases of doubts, i.e. if the D-regions appear to dominate against the B-regions, the method described in sect. 4.2 should be followed.

As already mentioned, for calculating the deformations and, in case of a statical indeterminate structure, the sectional effects, one will certainly start applying sectional values (bending stiffness EI, torsional stiffness GI_t, axial stiffness EA etc.) on linear-elastic basis.

If the sectional forces are known the dimensioning of the B-regions, especially of their reinforcement may follow standard procedures. As long as a section is uncracked (e.g. in columns or due to prestress), the inner forces are calculated with the help of section properties like cross sectional areas and moments of inertia. If the tensile stresses exceed the tensile strength of the concrete the truss model[1] applies (fig. 2). Since for B-regions with light transverse reinforcement, the truss model yields unrealistic low inclinations for the struts, efforts have been made to explain the mechanical meaning of the V_c-term, applied for correction by several codes, because the inclined compression chord explanation can apply only to D-regions. It has been shown by several authors and a paper by Reineck submitted for this Colloquium will go further into details, that by considering the concrete tensile strength it is possible to model the load bearing behaviour of the webs of a B-region consistently /7/.

The overall analysis and the B-regions dimensioning provide also the boundary forces for the D-regions of the same structure. As long as the D-regions are uncracked, they can be readily dimensioned and analyzed by standard procedures including finite elements analysis (FEA) applying Hooke's law. If they are cracked the STM design has to be applied for dimensioning /4,5,6,8/. For finding the geometry of the strut-and-tie-models especially for unusual cases, an elastic analysis on FE basis is helpful (Table 2). The loadpath method supports the finding of the model geometry and trains the designer's understanding of the flow of inner forces /5,6,10/. However, the number of D-region types for beams and frames is rather limited and the experienced designer will soon be able to rely on his STM-collection. Efforts are being made to provide practice with a reliable collection of such cases (further comments on D-regions see sect. 4.2).

1.Here the expression truss model is used to define the special application of the general STM to B-regions. A truss has compression and tension chords parallel to the surface lines, inclined struts or compressive stress fields and transversal ties representing the stirrup reinforcement and/or tensile stress fields.



$$C_c(x) = \frac{M(x)}{z} - \frac{V(x)}{2}\cot\theta$$

$$C_w(x) = \frac{V(x)}{\sin\theta} \longrightarrow \sigma_w(x) = \frac{V(x)}{b\,z\cdot\sin\theta\cos\theta} \text{ (smeared diagonal stress)}$$

$$T_w(x-\tfrac{a}{2}) = V(x) \longrightarrow t_w(x-\tfrac{a}{2}) = \frac{V(x)}{z\cdot\cot\theta} \text{ (per unit length of beam)}$$

$$T_s(x) = \frac{M(x)}{z} + \frac{V(x)}{2}\cot\theta$$

$V(x)$ may include shear forces from torque M_T

c)

Fig. 2: Truss model of a beam with cantilever: (a) model; (b) distribution of inner forces; (c) magnitude of inner forces derived from equilibrium of a beam element.

Table 2. Analysis leading to stresses or strut-and-tie-forces

Structure / Analysis		Structure consisting of:		
		B- and D-regions e.g., linear structures, slabs and shells		D-regions only e.g., deep beams
		B-regions	D-regions	D-regions
Overall structural analysis (Table 3) gives:		Sectional effects M, N, V, M_T	Boundary forces: Sectional effects	Boundary forces: Support reactions
Analysis of inner forces or stresses in indivdual regions	State I (uncracked)	Via sectional values A, J_B, J_T	Linear elastic analysis* (with redistributed stress peaks)	
	State II (cracked)	Strut-and-tie-models and/or nonlinear stress analysis *		
		Usually truss		

* May be combined with overall analysis

For later improvement and review and with the real dimensions and reinforcement in hand, it may be necessary to repeat the analysis using non-linear moment-curvature relations. This will become a must for structures with strongly geometrically non-linear behaviour, with theory of second order effects or in case of buckling problems. Fortunately there are handy computer programs available today for that purpose.

It must indeed be warmly welcomed, that most instability problems can today be solved by a theory of second order analysis on basis of imperfections, whose assumption poses no problem to the experienced designer.

Finally as an overall review for statically redundant structures, there are further "closed" methods. After the above-mentioned revision of the sectional forces the designer has the choice to repeat a dimensioning with strut-and-tie-models, or to apply one of the "closed" methods as contained in table 3, mainly a plastic analysis with plastic hinges for finding the overall load capacity or a sophisticated non-linear FEA, which contains not only the non-linear material behaviour but also a realistic failure hypothesis.

Table 3. Overall structural behavior and method of overall structural analysis of statistically indeterminate structures

Limit state	Overall structural behavior	Corresponding method of analysis of sectional effects and support reactions: Most adequate	Acceptable
Service-ability	Essentially uncracked	Linear elastic	——
	Considerably cracked, with steel stresses below yield	Nonlinear	Linear elastic (or plastic if design is oriented at elastic behavior)
Ultimate capacity	Widely cracked, forming plastic hinges	Plastic with limited rotation capacity or elastic with redistribution	Linear elastic or nonlinear or perfectly plastic with structural restrictions

4.2 Models for structures consisting of D-regions only e.g. deep beams

In this case the analysis of sectional effects by a statical system makes no sense anymore and the inner forces or stresses can be determined directly from the applied loads following the principles outlined for D-regions above, already.

In /5,6/, where the modelling and dimensioning of D-regions with STM is described in all details, it is proposed to orientate the geometry of the STM at the elastic stress fields, which means to utilize the same model for the serviceability and the ultimate stress check (fig. 3). Of course this does not exclude adjusting the model geometry whilst approaching failure towards an increase of the internal lever arms (fig. 4).

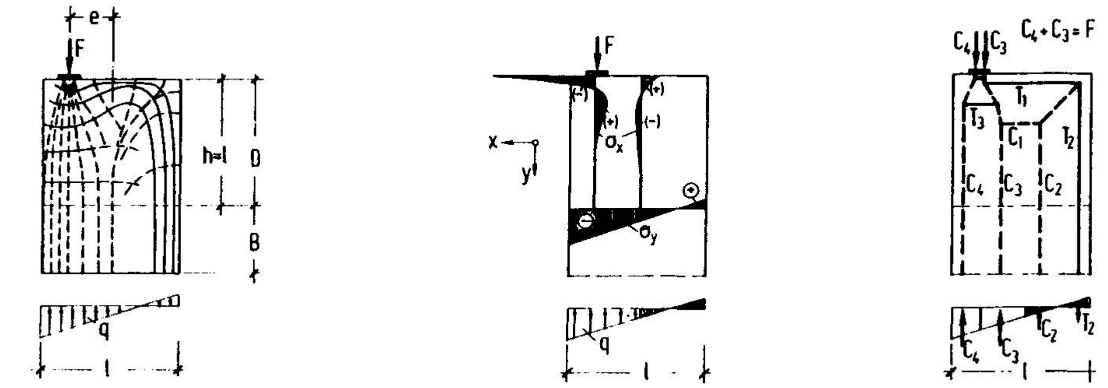


Fig. 3: A typical D-region: (a) elastic stress trajectories; (b) elastic stresses; (c) strut-and-tie-models.

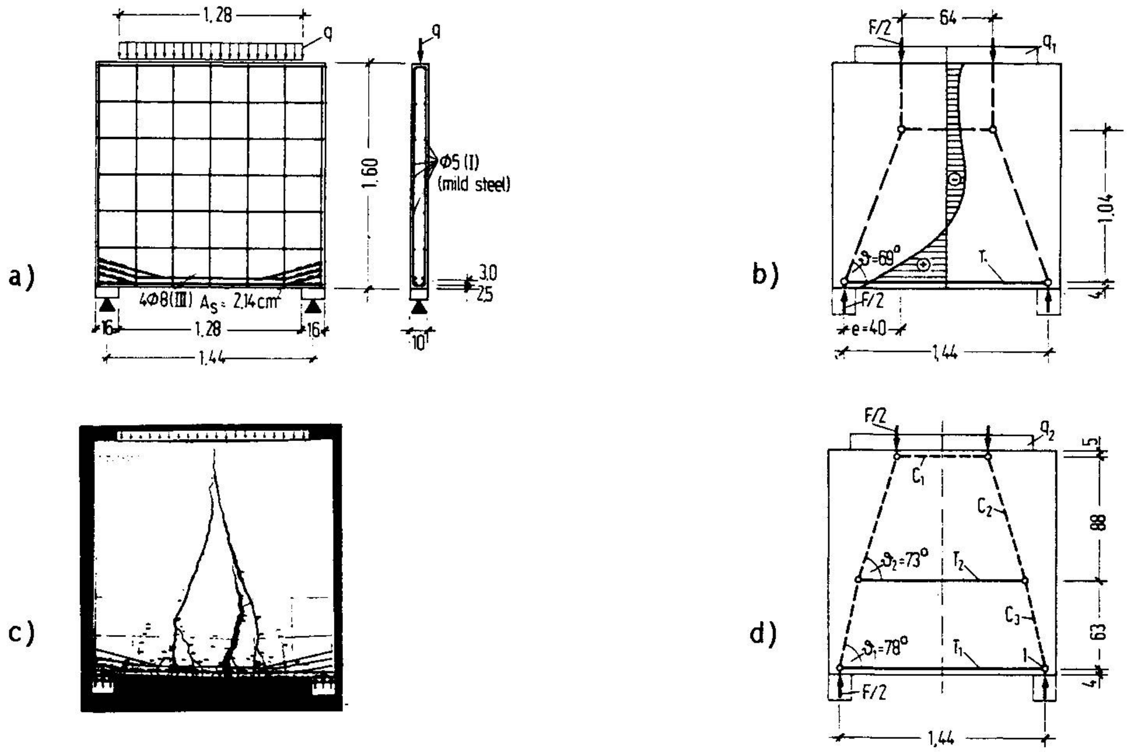


Fig. 4: Deep beam: (a) Tested specimen WT2 /16/; (b) model oriented at the theory of elasticity; (c) crack pattern from test; (d) model adjusted to the failure mechanism.

The designer will decide in the individual case, whether he finds his STM on his own, where the "load-path method" will be a valuable tool (fig. 5), or if he wants in a more complicated case to start with a linear elastic FEM analysis (fig. 6).

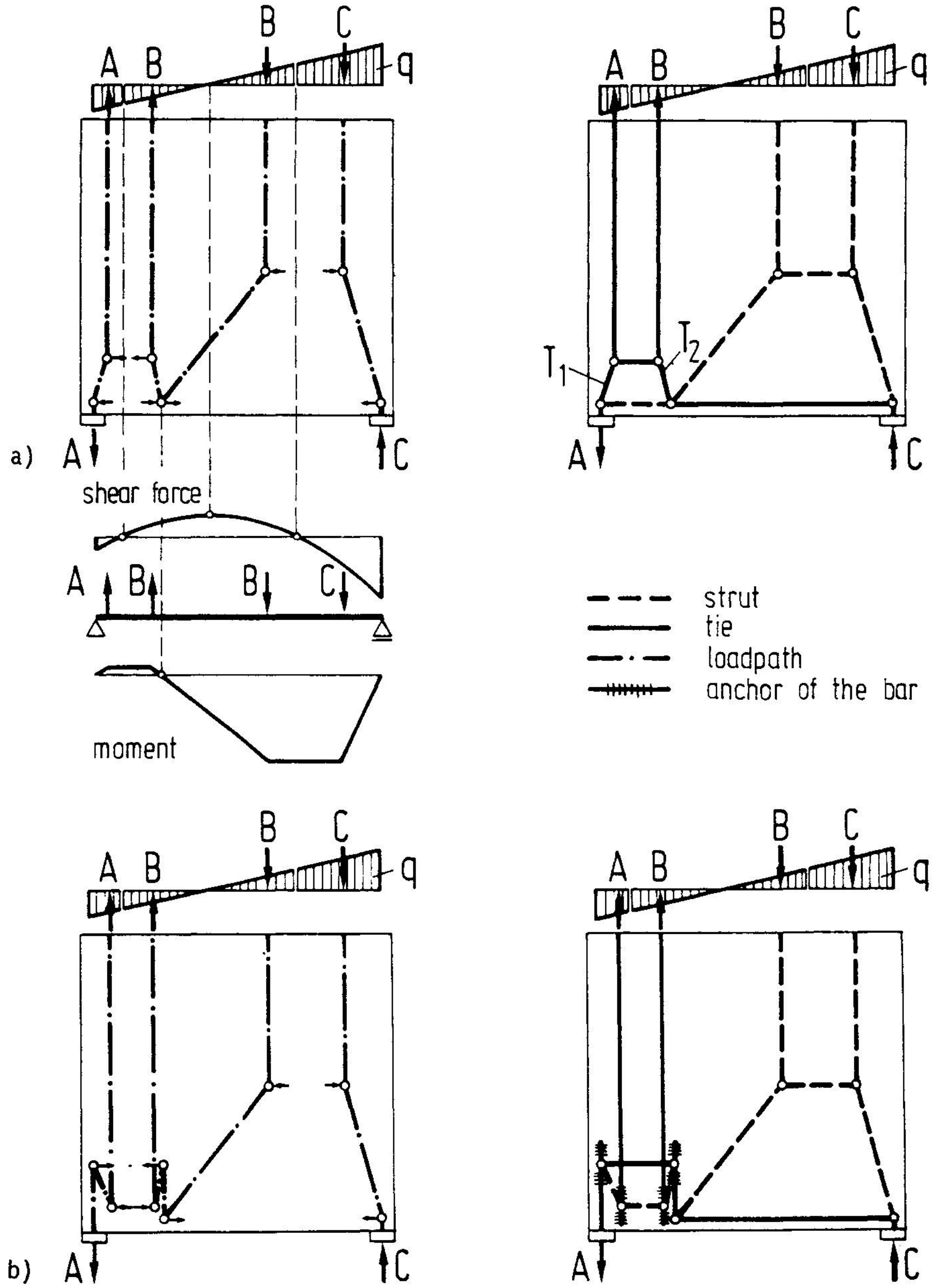


Fig. 5: Application of the load path method for finding the appropriate strut-and-tie-model. Two models for the same case: (a) requiring oblique reinforcement; (b) for othogonal reinforcement.

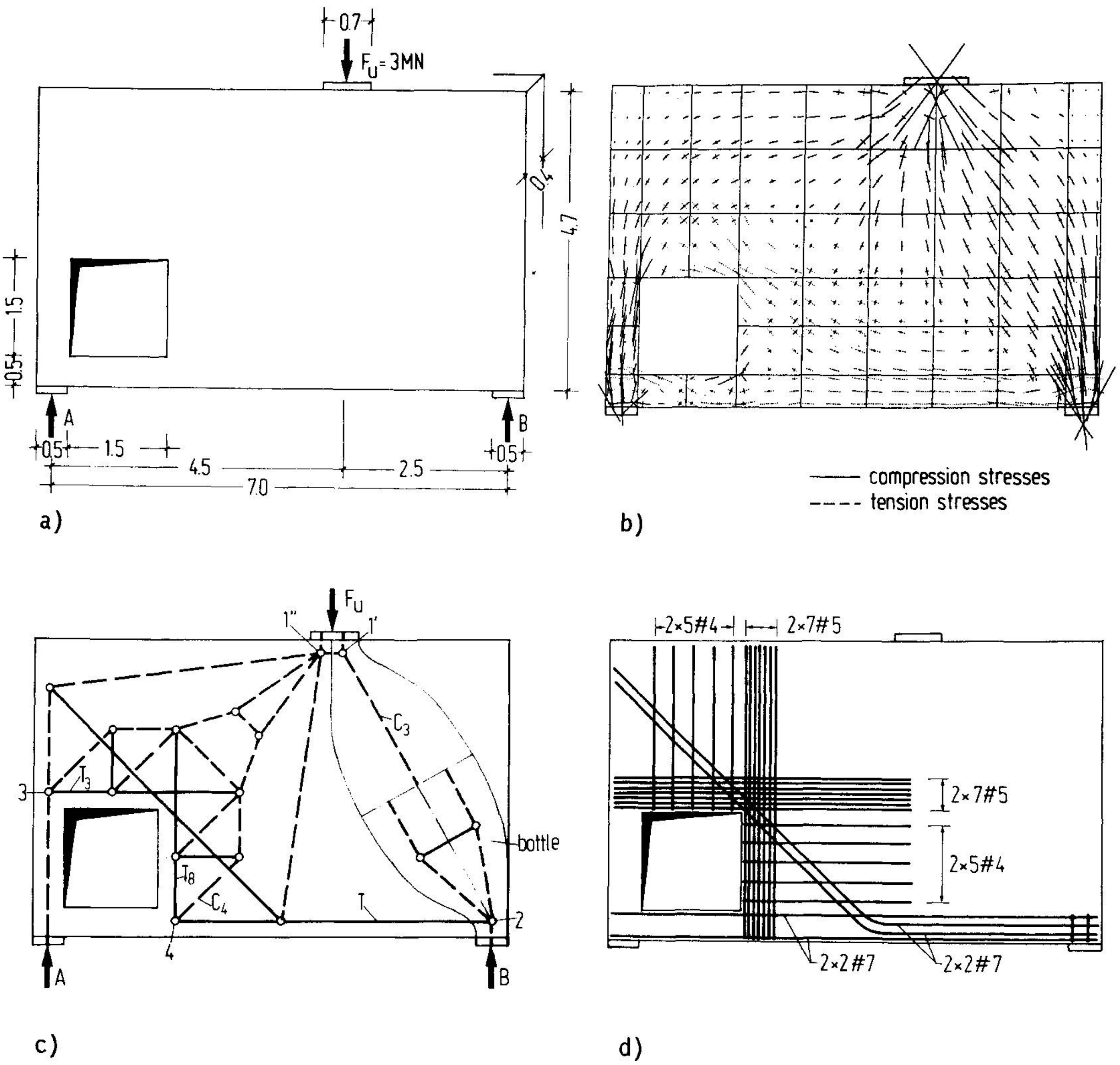


Fig. 6: Deep beam with a large hole. (a) dimensions /m/ and load; (b) elastic stresses; (c) complete strut-and-tie-model; (d) reinforcement.

Recently the fact that the STM-dimensioning is a combined graphical and analytical method has led to very useful CAD programs, which permit to develop, optimize and dimension STM on the screen /9,10/. This also opens the door to not only dimensioning D-regions but also to analyse them by attributing non-linear constitutive laws to the struts and ties thus being able to evaluate the deformations and the redundant inner forces for statically indeterminate supported deep beams /11/. Comparisons of such analyses with test results on the one, and non-linear FEA on the other did yield promising results. Rückert and Sundermann will specify that further during the Colloquium.

There has been some dispute on the so-called ambiguity of the STM, mainly from code-makers running after cookbook recipes. It's not the STM, it's reinforced concrete itself, which has fortunately the capability to adjust its inner flow of forces to the designer's reinforcement layout. A complex and intelligent material belongs into the hands of an experienced designer. He will find the right STM for his specific case and will keep serviceability and ductility requirements in mind, when optimizing it towards ultimate load capacity.

Fortunately there is a lot of progress with the non-linear FEA of cracked reinforced concrete /12/. A. Scordelis will come back to that during his invited lecture on analysis. Thus the designer has the tool to review his STM results, from which he of course has to collect the reinforcement layout before doing a FEM check. Comparing both results will have a high pedagogical value and avoids misinterpretations of black-box computer outprints.

Such a procedure should be followed as a golden rule: Dimensioning on basis of relatively simple models, thereafter rewiew on a suitable level of sophistication.

Non-linear FEA appears to be of special value, if the overall deformational behaviour of a deep beam or the reactions of a statically indeterminate supported deep beam structure is asked for. It will also be able to describe and clearly trace failures of concrete in compression or tension as well as of the reinforcement. For that of course it must be possible to model the real crack pattern, especially discrete cracks often responsible for failure. But doubts arise with respect to its capability of describing the behaviour of nodes. For that purpose it would be necessary to computerize the concrete at a microlevel i.e. to follow with the finite elements down to the gravel and reinforcement ribs.

From that it follows, that even a FEM analysis should be followed by a STM check especially with respect to the safety of the nodes (fig. 7).

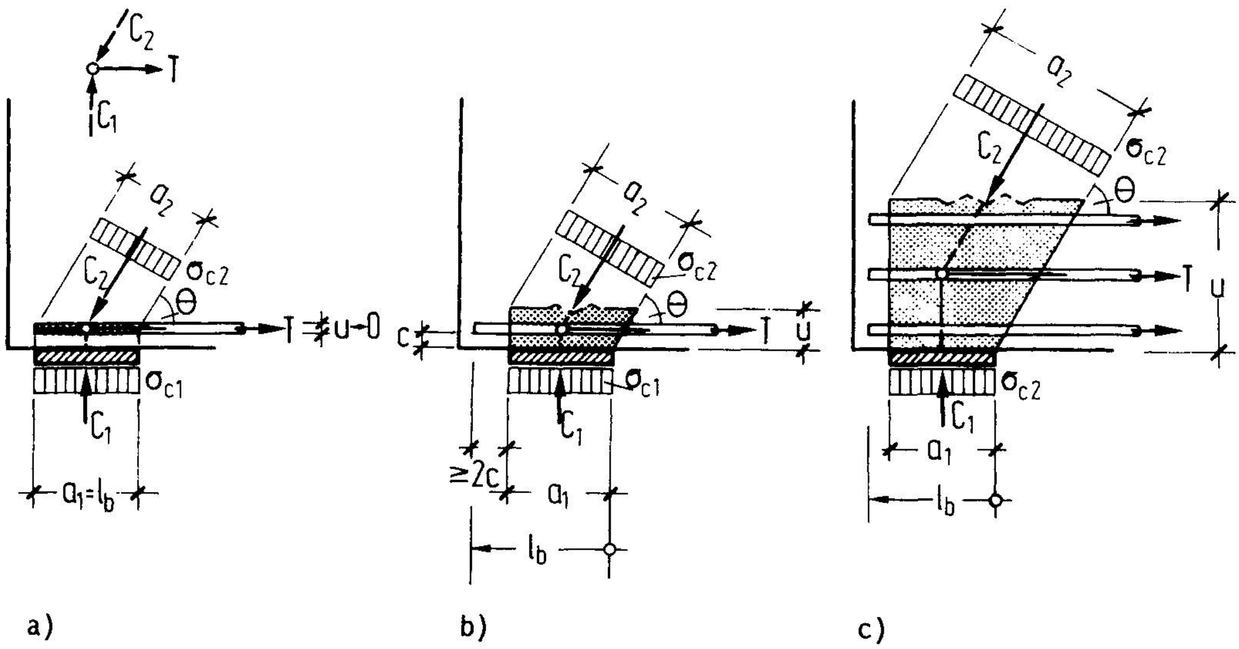


Fig. 7: Typical node for the anchorage of reinforcement; (a) one layer; (b) one layer with additional length behind the node; (c) three layers with additional length behind the node.

4.3 Models for slabs and folded plates

Since these structures may as well be sub-divided into B- and D-regions, the same models and methods as discussed above may be applied as well. In fact they predominantly consist of B-regions (plane strain distribution). Starting from the sectional effects of the structural analysis, imaginary strips of the structure can be modelled like linear members.

However, it would be desireable to develop a real STM approach which considers that the principal moments and forces of slabs do not follow straight lines parallel to the edges.

Further there is no satisfactory model as yet describing punching of slabs. For the large variety of slab shapes with all kinds of openings it is very helpful, that today FEM programs on linear-elastic basis are available to any designer. Since slabs rarely do reveal substantial cracking, it may not be very desirable to repeat such an analysis with non-linear FEM. Rather will an overall ultimate capacity check by means of the yield line theory provide useful additional information.

4.4 Treatment of prestress

In a paper on modelling of structural concrete, a word on the treatment of prestress may be expected. However, it appears sufficient to mention that consistency between reinforced and all "types" of prestressed concrete can easily be reached if for the analysis of the sectional forces prestress is simply treated, what it really is: a self-equilibrated outer load, though artificially applied. Whilst dimensioning, its forces are treated as are other forces. After grouting the prestressing steel will then assume the role of reinforcement (with an initial prestressing force and with special properties).

In case of prestress without bond or of external prestress after prestressing the tendons take the role of free ties whose changes of forces due to loads may be estimated or analysed on basis of a statical indeterminate system /5, 15/. Jennewein, in a contribution to this Colloquium will give further evidence of that.

With this the same models and methods as already discussed apply also to the case of prestress (fig. 8). This treatment helps to avoid useless discussions as those, whether the statical indeterminate moments due to prestress are restraint forces which disappear due to cracking or not. Of course they are not, they are moments as those due to any other outer loads which cannot dissappear but of course be redistributed. This view of prestress is a valid basis for the consistent treatment of structural concrete and for a simplification of codes.

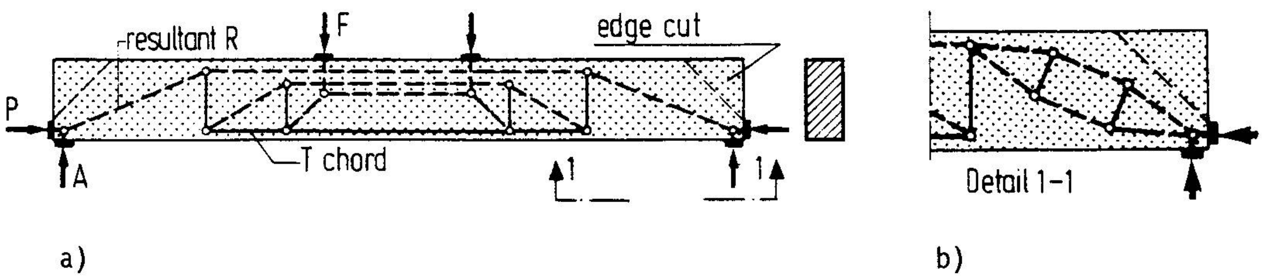


Fig. 8: (a) Strut-and-tie-model of partially prestressed beam with rectangular cross section; (b) detailed strut-and-tie-model of the beam area, where the resultant is within the beam section.

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