A SOLUTION FOR WALLS AND DETAILS OF CONCRETE STRUCTURES





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Abstract

Every concrete structure has several parts with some form of discontinuity - bracket, opening, anchorage, etc. In spite of discontinuity regions being present in every concrete structure, no single solution exists so far for complete design of concrete details, walls and diaphragms. Single-purpose, specialized programs or Excel design sheets based on Strut-and-Tie Method are currently used for the design of discontinuity regions. Conversely scientifically oriented programs might exceptionally be used with no link-up with national standards and regulations, and without design and optimization of reinforcement. This practice leads to oversimplifications or on the contrary to the attempt to simulate reality. A new method and a software tool allow engineers to design appropriate concrete dimensions as well as location and amount of reinforcement in an efficient way, providing safe and economical designs based on valid standards. It is based on a computer-aided implementation of stress field models. Simplified assumptions similar to the ones used in hand calculations are used, improved to allow ductility and SLS verifications, and based on clear material properties. Stress fields can be seen as a generalized Strut-and-Tie Method in which real members with stresses instead of force resultants are considered. The verification has been done against code independent cases as well as against existing codes with material laws as defined in the codes.

Key words: Concrete, Wall, Detail, Discontinuity, Reinforcement

1 Introduction

Design and assessment of concrete elements are normally performed at sectional (1D-elements) or point (2D-elements) levels. This procedure is described in all standards for structural design, and it is used in everyday practice of a structural engineer. However, it is not always known or respected that it is acceptable only in areas where the Bernoulli - Navier hypothesis of plane strain distribution applies (referred to as B-regions). Places, where this hypothesis does not apply, are called discontinuity or disturbed regions (D-

Regions). Examples of B and D regions of 1D-elements are given in Fig. 1. These are e.g. bearing areas, parts where concentrated loads are applied, locations of an abrupt change in the cross-section, openings, etc.

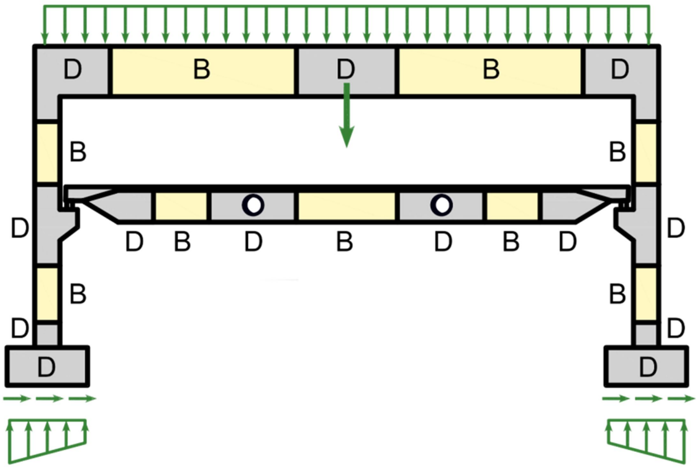


Fig. 1 A structure containing B and D regions

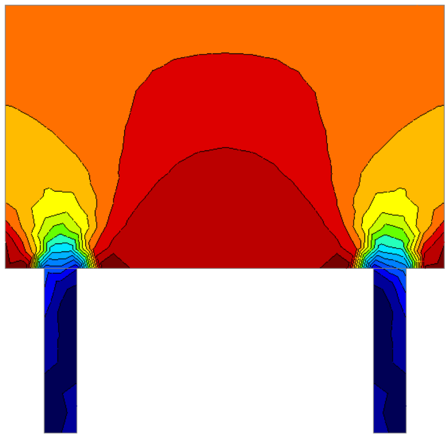


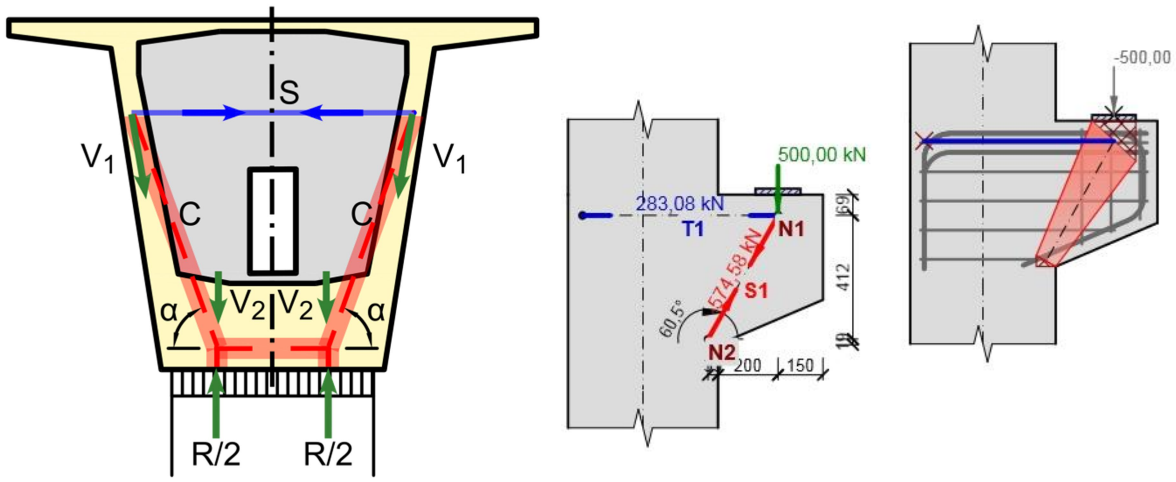
Fig. 2 D-Regions in the transition of the column support system to the wall

D-Regions also occur on wall elements of cast-in-place and prefabricated objects. Although linear-elastic models used in the present practice reveal this fact, see Fig. 2, they are unable to give a true picture of stiffness reduction, stress redistribution due to cracks, tension stiffening, compression softening of concrete, etc. The result of linear-elastic analysis is a color image of unrealistic internal forces and stresses with irresistible peaks, which is useless for the engineer. Application of such results often leads to overestimation of structural stiffness, crack formation and excessive deflection.

An example may be an exterior facade walls with window openings. Albeit also linear-elastic calculation shows high stress concentrations at the corners of the headers, the results are incomprehensible, and do not provide a hint for how to position the reinforcement, which leads to cracks in the parapet walls. Problems also arise, for example, in the transitions of the column support system to the wall, see Fig. 2. The high pressure in the columns combined with the insufficient transverse reinforcement of the wall causes the wall to be transversely distorted, the columns punch through it, and almost vertical cracks occur.

2 Methods for design of walls and discontinuity regions

It is possible to use sophisticated programs that work with nonlinear computational models and methods in case of complicated problems of building practice. These methods, however, can hardly be used for conceptual design of structures or structural details. They require to have pre-designed the dimensions of members, and also positions, directions and amount of reinforcement. In addition, they are still very challenging in terms of necessary time and user experience. It is necessary to correctly choose material models and their parameters, which the user often does not understand and for time reasons or for lack of knowledge he does not make the necessary verification and validation of these models. For this reason, results can often be very different from reality. It is also very difficult to interpret the results in terms of standard provisions. In fact, the models try to capture virtual reality rather than standard code assessment. Although stochastic methods based on probabilistic principles have been developed for these purposes, their demandingness is even higher and unacceptable in practice.



(a) Diaphragm of box-girder bridge (b) Bracket in IDEA StatiCa [2] according to [1]

Fig. 3 Practical examples of Strut-and-Tie Method

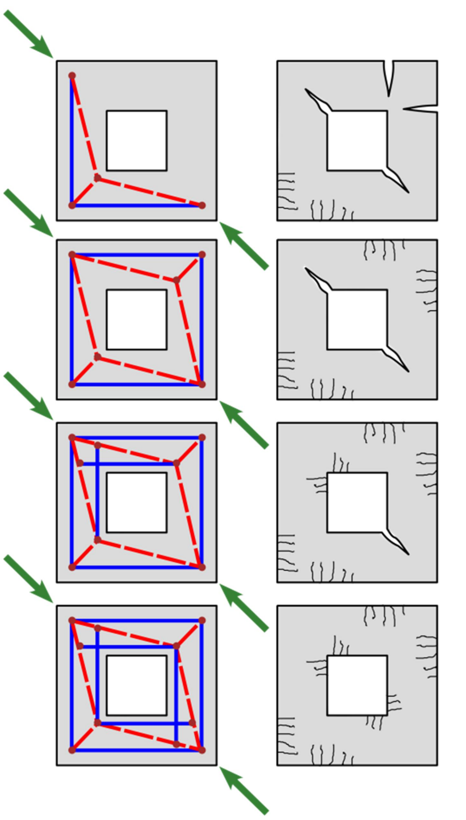


Fig. 4 Demonstration of the variety of "correct" truss models

Therefore, D-Regions are currently most often designed using the truss analogy (Strut-and-Tie Method). Based on structural shape, load, and boundary conditions, the engineer proposes a substitute truss model, on which he then determines the load-bearing capacity of concrete struts, nodal areas and reinforcement (ties). The method is very simple; the truss model calculation is fast and can be easily done. There are many models proven by good practice and recommended by standards, see Fig. 3.

However, the method also has a number of disadvantages. Especially with regard to the simplification of the truss model, only the ultimate limit state (ULS) can be checked. The assessment of crack width, stress limitation and deflection is impossible using this method. This disadvantage becomes a considerable constraint due to the increasing emphasis on serviceability limit state design (SLS).

Another disadvantage is the ambiguity in creation of a suitable truss model. There are an infinite number of possible truss models, but only one of them is optimal and there is no guaranteed way to identify it, see Fig. 4. When creating the model, we must first recognize the coherence of (i) the design of member or its detail with (ii) its computational model. The design of shape, dimensions and reinforcement determines the behavior of the structure and also the mode of failure. We usually know the "weak" links in the structure in advance, or we predetermine them deliberately. Thus we in fact create the model of the structure in the ultimate limit state.

A good example is a deliberate under-sizing of the reinforcement in the cross-section above the support of a continuous beam that, together with a sufficient reinforcement in the middle of the spans, results in the redistribution of moments. The creation of the model must respect among others the fact that the tensile strength of the concrete is practically zero and that the same is true for the flexural resistance of the concrete itself as well. Therefore, if the concrete is attributed with the ability to transfer just the compressive forces and the steel with the ability to transfer only the tensile forces, we get a very simple truss model consisting of elements exclusively under tension or compression. The strut and tie model must express the behavior of the structure in the limit state. The creation of the model thus cannot be accidental, but it must correspond to the conditions of the lower bound and upper bound theorems. The impact of rebar positions on mode of failure and crack propagation can be demonstrated on the example in Fig. 4. The author's experience is that even professionals have inadequate knowledge of the main principles for the creation of the models in cases of atypical details.

3 Safe and economic design

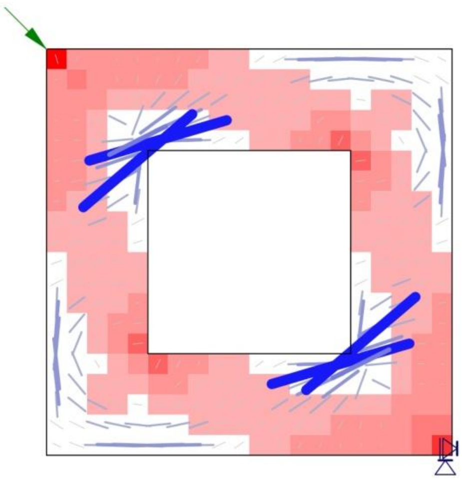
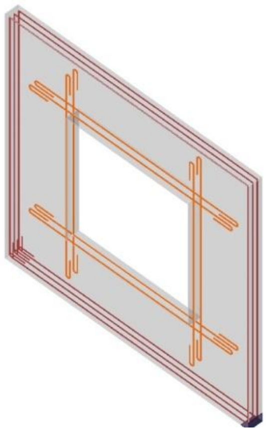


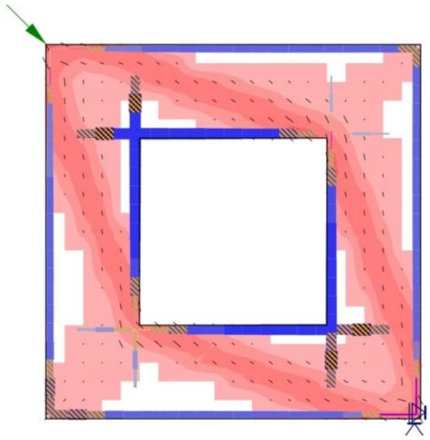
Fig. 5 Identification of truss model

The interest of structural engineers in a reliable and fast tool to design D-Regions has led to the decision to develop new computational software for the design and assessment of details and walls of reinforced concrete structures, which is commercially available under the name IDEA StatiCa Detail [2]. This program combines the benefits and eliminates all the above shortcomings of the methods described in the previous chapter.

The first advantage of the method, which is particularly relevant for atypical details and wall structures, is the possibility of designing the positions and directions of reinforcement by the topology optimization method, see [4], or alternatively by linear analysis, see Fig. 5. In particular, the design of the truss model by topology optimization identifies optimal reinforcement locations and directions, which can greatly assist the structural engineer in deciding how to reinforce the structure. No commercial tool used so far provides such a feature.



(a) Positions of reinforcement

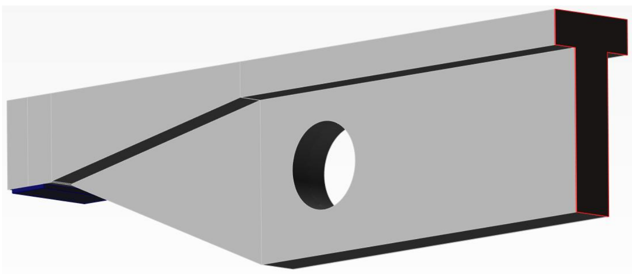


(b) ULS check - stress fields, reinforcement and anchorage

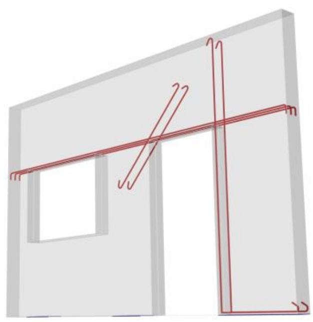
Fig. 6 Wall panel with an opening in IDEA StatiCa [2]

4 Assessment based on valid standards

Similarly to the Strut-and-Tie Method, the specification of input data, reinforcement design, the analysis, and the code assessment are very fast and can be done, contrary to general nonlinear programs in the order of 10 to 20 minutes. The model has been verified and validated, including all parameters entered into the calculation, by the prestigious Institut für Baustatik und Konstruktion, ETH Zürich [3], [5]. Therefore no special experience or knowledge is needed to understand the input values and the results. The assumptions of the solution are above the models recommended by national standards. However, all results are fully interpreted in terms of code provisions [1]. Therefore the solution is code independent and at the same time code complying. The methods used for the calculation and assessment are general both in terms of structural topology, see Fig. 7 and the results provided, see Fig. 8. The results are comprehensible and reflecting reality to the full extent. They can serve not only for the assessment of ULS, but also for SLS including crack widths, deflections and stress limitations. Note that SLS checks have not been fully implemented yet. Auxiliary results in the form of zones of excessive tensile concrete strains can be used to help with the assessment of crack width check in the first version of the program.

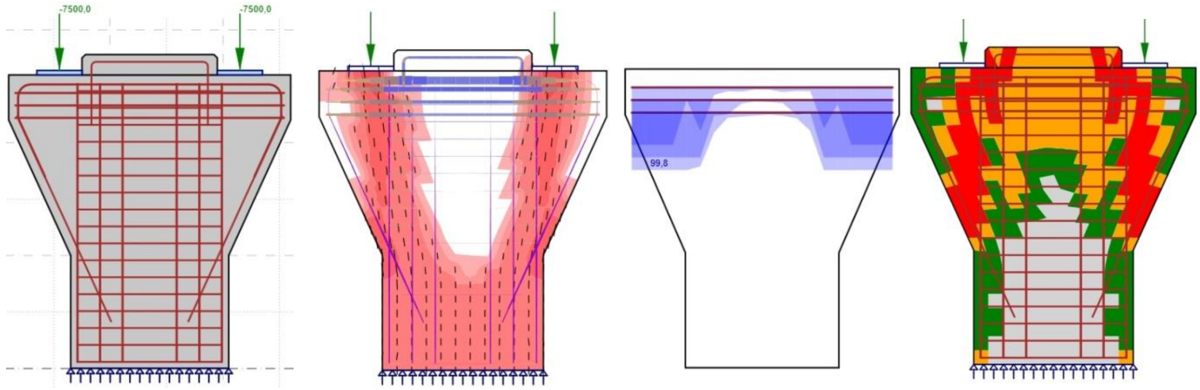


(a) Combination of dapped end with the haunch and opening



(b) Wall with openings

Fig. 7 General topology of discontinuity regions



(a) Load and reinforcement (b) ULS check (c) Anchorage (d) Tensile strains

Fig. 8 Pier cap of bridge structure

5 Conclusion

Structural analysis and design of concrete structures is a challenging task – both because of the natural complexity of the subject and because of the regulation an engineer has to comply with to get the project done. The construction process has never been as fast as it is today, and the pressure on cost-effectiveness of structures is growing with zero tolerance of structural defects. In such an environment, engineers are pushed to work quicker, more accurate and more reliably than ever before. And they need a different set of tools for that.
The development trend of IDEA StatiCa is to provide engineers with a generic, complete, and easy-to-use solution for designing and dimensioning structural elements, cross-sections and details in accordance with applicable standards. We believe that IDEA StatiCa Detail provides a solution on the level of advanced non-linear programs, but at the same time it will be commonly used for day-to-day practical design.

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