Design and analysis with strut-and-tie models: computer-aided methods

Design and Analysis with Strut-and-Tie-Models – Computer-Aided Methods

Méthodes assistées par ordinateur pour la conception basée sur l'analogie du treillis

Methode der Stabwerkmodelle: Umsetzung in einem Computerprogramm

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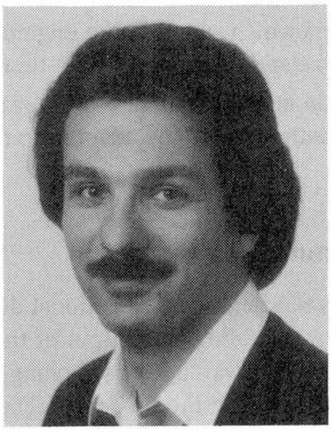

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SUMMARY

The design method for strut-and-tie models was implemented in a computer program both to increase user-friendliness and to use the graphical and numerical capabilities of the computer. Therefore, a program system was developed which consists of several independent modules, which are linked through interprocess-communication and which run under a uniform user interface. The strut-and-tie model method was extended especially in the fields of: Modelling (strut-and-tie models can automatically be constructed out of trajectory fields) and Analysis (the use of a nonlinear analysis program together with nonlinear material laws and an algorithm for optimization, allows to calculate forces and displacements for the design as well as for the serviceability state).

RÉSUMÉ

La méthode de conception qui se base sur l'analogie du treillis a été traduite par un programme d'ordinateur afin d'augmenter le confort de l'utilisateur et de profiter des capacités graphiques et numériques de la machine. Le programme qui a été développé dans ce but comprend plusieurs modules indépendants liés à une méthode de communication interactive faisant l'interface avec l'utilisateur. L'analogie du treillis a été spécialement étendue dans les domaines de la modélisation (à partir du champs des trajectoires, on peut construire automatiquement des modèles de treillis) et de l'analyse (un programme d'analyse non-linéaire permet, conjointement aux lois non-linéaires de comportement des matériaux et d'un algorithme d'optimisation, de calculer forces et déplacement nécessaires au projet, aussi bien que pour l'évaluation de l'état de service).

ZUSAMMENFASSUNG

Die Methode der Stabwerkmodelle wurde in ein Computerprogramm umgesetzt, um die Benutzerfreundlichkeit zu erhöhen und die grafischen und numerischen Möglichkeiten des Rechners auszunützen. Dafür wurde ein Programmsystem entwickelt, das aus mehreren unabhängigen Modulen besteht, die durch Interprozess-Kommunikation gekoppelt sind und unter einer einheitlichen CAD Benutzeroberfläche ablaufen. Die Methode der Stabwerkmodelle wurde insbesondere erweitert auf den Gebieten der Modellfindung (aus Trajektorienfeldern können automatisch Stabwerkmodelle abgeleitet werden) und der Berechnung (durch Verwendung eines nichtlinearen Rechenprogrammes zusammen mit nichtlinearen Materialgesetzen und einem Optimierungsalgorhythmus können realistische Kräfte und Verformungen sowohl für die Bemessung als auch für den Gebrauchszustand berechnet werden).

1. Introduction

During the last years the strut-and-tie model (STM) design was developed as a method to unify the design of structural concrete for all kinds of concrete members and details /1,2,3/. One can consider this method as a combination of graphical and analytical techniques which had traditionally been applied 'by hand'. As the development and application of hard- and software has proceeded rapidly in the last years and a computer is on nearly every desk, it became clear that this method should also benefit from the graphical and numerical capabilities of the computer /7,9/ since a programm based on a consistent design concept would be more logical for a CAD program than the effort to program only codes. Developments took place at different locations in various directions, i.e. based on theory of plasticity /5/.

The goal of bringing the strut-and-tie models 'onto the computer' included the following two tasks:

- Development of a program system which supports the engineer in an easy to use, graphical manner and allows to display, input, edit, analyze and design strut-and-tie models on a workstation.
- Enhancement of the strut-and-tie model method, especially in the fields of model finding and calculation of forces and displacements. The method had to be adapted to the computer, but this yielded also new possibilities.

2. Development of the Program System

The overall design process includes the fields of conceptional design, idealization of the structural model, analysis, design of the structural members, detailing and output of the drawings. Specialized programs exist for each of this fields with the user having the disadvantage of switching between different programs and the difficulty of transferring and translating the data between the programs. There was no integrated system which supports not only single steps but the whole process. To fulfil this requirement the developed integrated system needed the following modules within 'one' program:

- A CAD program to draw and edit the models and drawings and to display the results of the calculations.
- A FE program to analyze the structures.
- Programs to design the structural members with the STM method.
- A database to save all input and calculated data for easy access through the other modules.
- A interactive graphical user interface and control program which allows ease of use, portability and expandability.

An 'automatic' program was surely not the goal, as '.. it is imperative that an experienced and qualified engineer be involved in the interpretation of the results using their knowledge of structural behavior ..' /9/. Therefore the program was developed as a toolbox or method-base of application programs which is used similar to a database. The user communicates with the program through a uniform user interface (the CAD program) and can choose among several ways (simple to more demanding) and modules according to the specific needs of the problem. The results of each step can be checked as they are immediately displayed on the screen and if needed can be calculated repeatedly. The user must not be concerned about the compatibility of the program modules and the integrity and transfer of the data as the program system takes care of this.

It was unreasonable to combine everything in one program because of program size, complexity and expandability with other modules. Therefore programming interfaces were developed for graphics, database and interprocess communication (IPC). All stand-alone programs (CAD, FE, design, ...) were only extended with these interfaces. The CAD program with its graphical capabilities for input, editing and output was used as the main and control program. The others, which can run invisible in different processes or windows, were linked to it through IPC and can exchange commands and data very quickly. By this way the programs can be developed (and used) separately and new or improved modules can be implemented easily. This structure is invisible to the user as he has the impression of only one single menudriven program. An overview of the program system is shown in Fig: 1 .

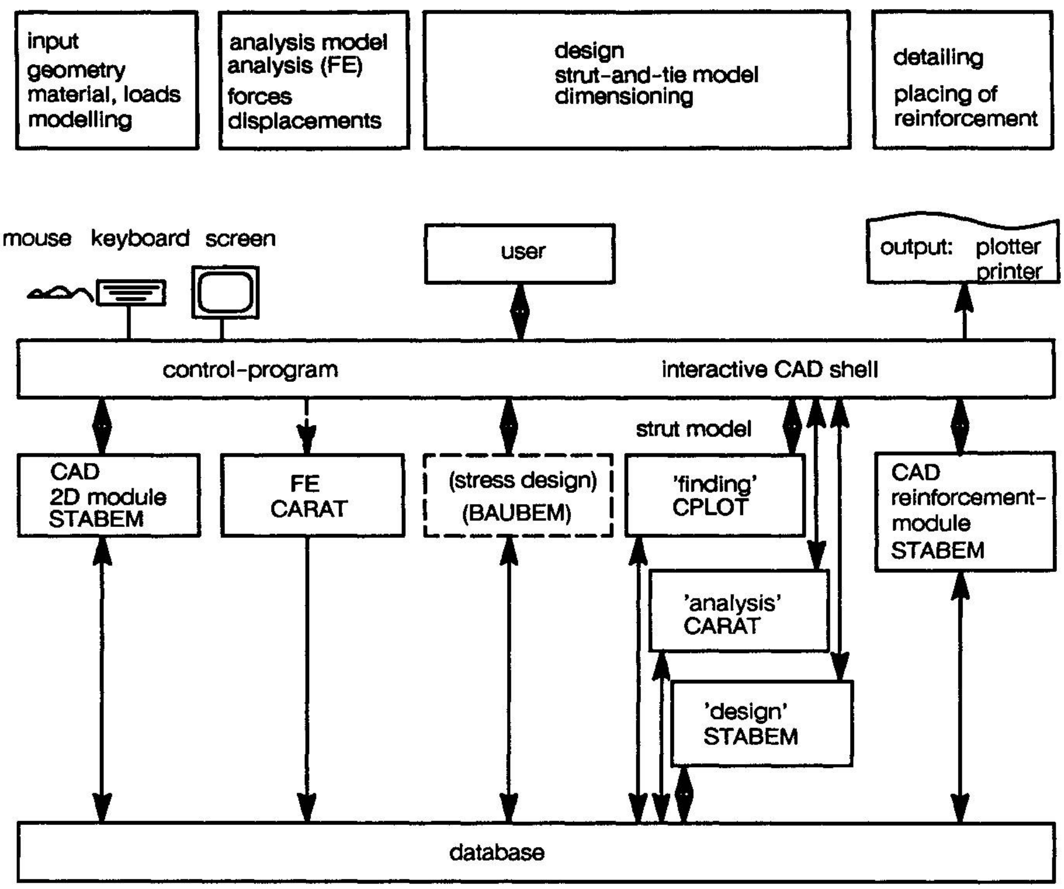

Fig. 1: Structogram of the program system

3. Strut-and-tie model design

3.1. Elements

The struts as basic elements represent both the resultant forces and the corresponding stress fields. In the design program they are therefore defined as truss elements with varying shapes (Fig: 2).

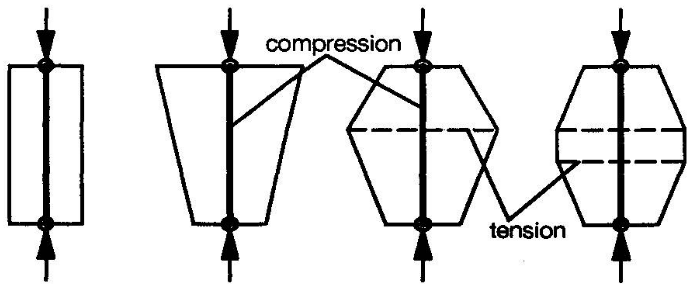

Fig. 2: Elements

The struts have dimensions according to the thickness of the structure and the width of the stress fields. This together with realistic material laws for concrete (compression and tension) and reinforced concrete (tension) allows the calculation of the nonlinear behavior (stress, strain, displacement, energy) of struts and ties.

3.2. Modelling

The finding of a suitable model is one of the most important points for the design as the model has to represent the actual flow of forces in the structure and is the starting point for all following calculations.

The simple modelling methods:
- 'free hand' drawing of simple models
- adaptation of known typical models to a specific case

are supported by the computer through the graphical drawing and editing possibilities and a 'database' of known models.

A simple preliminary elastic FE analysis of the structure helps the modelling methods:
- orientation of the model at the linear theory of elasticity,
- finding of the 'load path '

by underlaying the principle stress fields and possible calculations of stress resultants anywhere in the structure.

The most interesting and newly developed part is the model finding with trajectory fields. Trajectories can be generated at a desired density (which can but need not increase accuracy) and automatically be transformed into a strut-and-tie model (Fig:3). This represents a model which is closely oriented at the theory of elasticity and is inherently in a state of equilibrium.

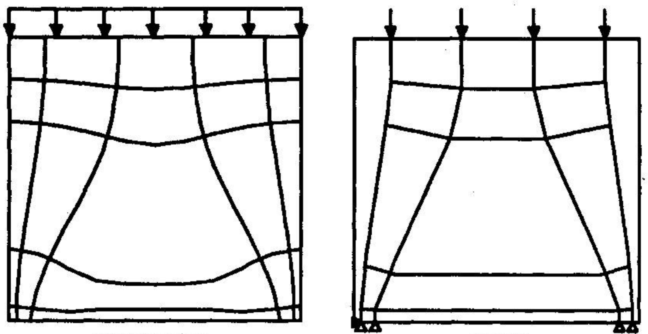

Fig. 3 : Strut model out of trajectories

The net of trajectories is equivalent to a 'shear free' net of (FE–) elements which have only biaxial normal stresses. It is possible to calculate the forces in a 'strip' bordered by two trajectories (Fig: 4). Therewith the 'flow' of forces in the structure (e.g. from the load to the support and perpendicular) becomes visible. These forces and their direction in the continuum are then equivalent to the forces and directions of the struts resp. stress fields and therewith the analogy between continuum and strut model becomes obvious.

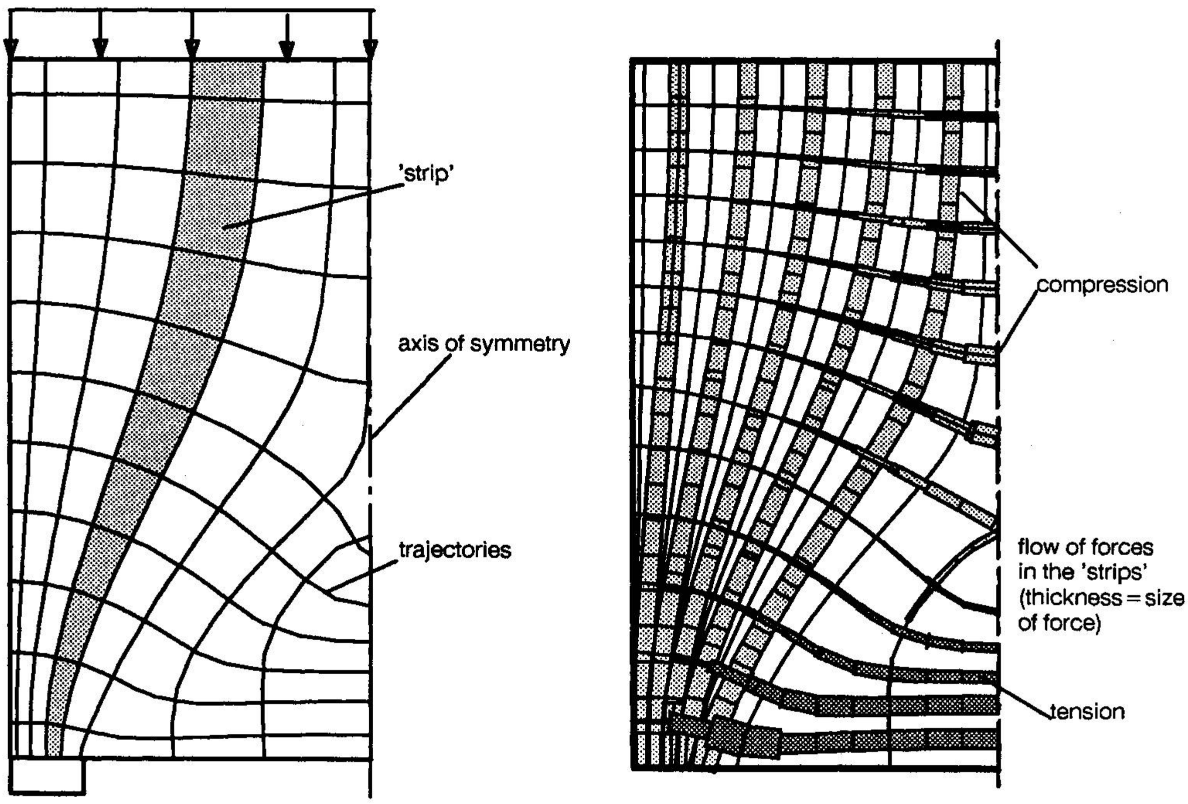

Fig. 4 : 'Trjectories and flow of forces'

The 'density' of the model is up to the designer and depends on the design stage /9/. Often it is sufficient for design purposes to use a simple model (Fig: 3) and leave the less important trajectories out. The program provides numerous possibilities to edit the automatically created model and to adapt it to the specific needs, as for example given positions and directions of reinforcement.

3.3. Analysis

For statically determinate and indeterminate models it is difficult to verify that they represent the load bearing of the structure as the geometry can be (almost) arbitrarily chosen. For kinematic models there is (for a given load) only one stable geometry which then reflects the load bearing.

The difficulty of analyzing a kinematic model was solved by using a geometric nonlinear program which was extended with initial stiffnesses to calculate 'kinematic cable structures' and which can therefore also be used to find a stable geometry (Fig: 5). If the model is generated through trajectory fields, the advantage is that it is already in a stable position and also represents the actual flow of forces.

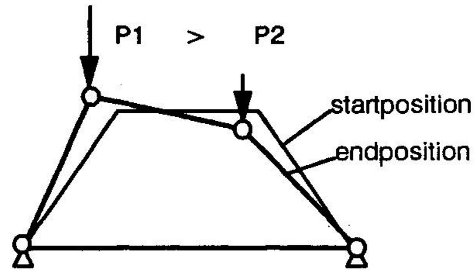

Fig. 5 : Analysis

The dimensioning of concrete and reinforcement is a relatively simple task and could for every model also be done by the theory of plasticity /4,5/. A model which is oriented at the theory of elasticity is both well suited for the design of struts and ties, as the calculated amount of reinforcement and concrete stresses are on the safe side according to the lower theorem of plasticity, and the requirements for compatibility and serviceability are also approximately fulfilled.

If however, one wants to know the state of stress or the displacements for any loading stage from cracking up to ultimate load, the geometry of the model has to be adapted to the load bearing behavior resp. 'load path' of this state. The struts must also have the according properties (width, material, etc.). The implemented strut elements with dimensions corresponding to the stress fields and nonlinear material laws allow the calculation of forces and stresses as well as displacements (Fig: 6)

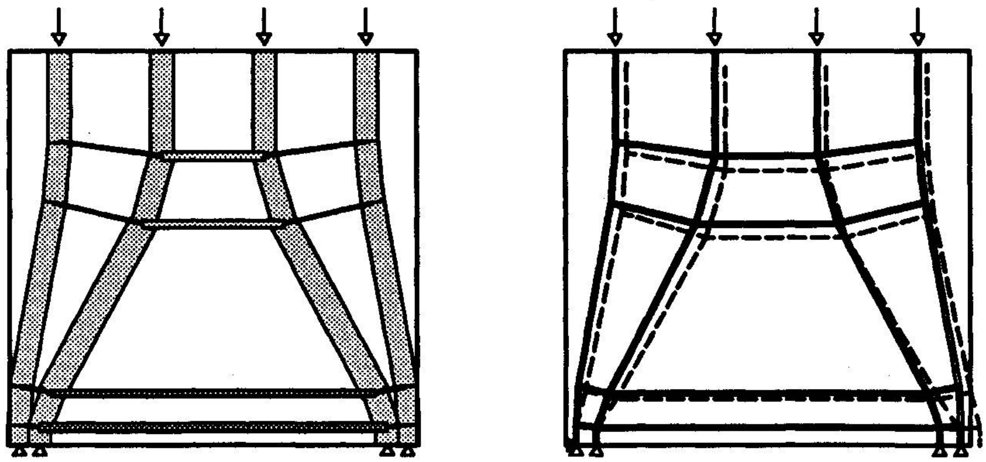

Fig. 6 : Forces and displacements

This is done with the criterion of optimizing/minimizing the internal energy of the total system as it tends to undergo the smallest possible stresses and strains. This together with an iterative nonlinear analysis allows to adapt the model, i.e. find the right geometry, for increasing loads as shown in Fig: 7 . Comparisons with tests show satisfying results.
This is a tool for the experienced engineer to achieve results for the design and its verfication in a rather simple and quick way. An additional nonlinear FE analysis for the verification (but not for the design itself) could still be done, but to achieve possibly better results it has to be much more elaborate.

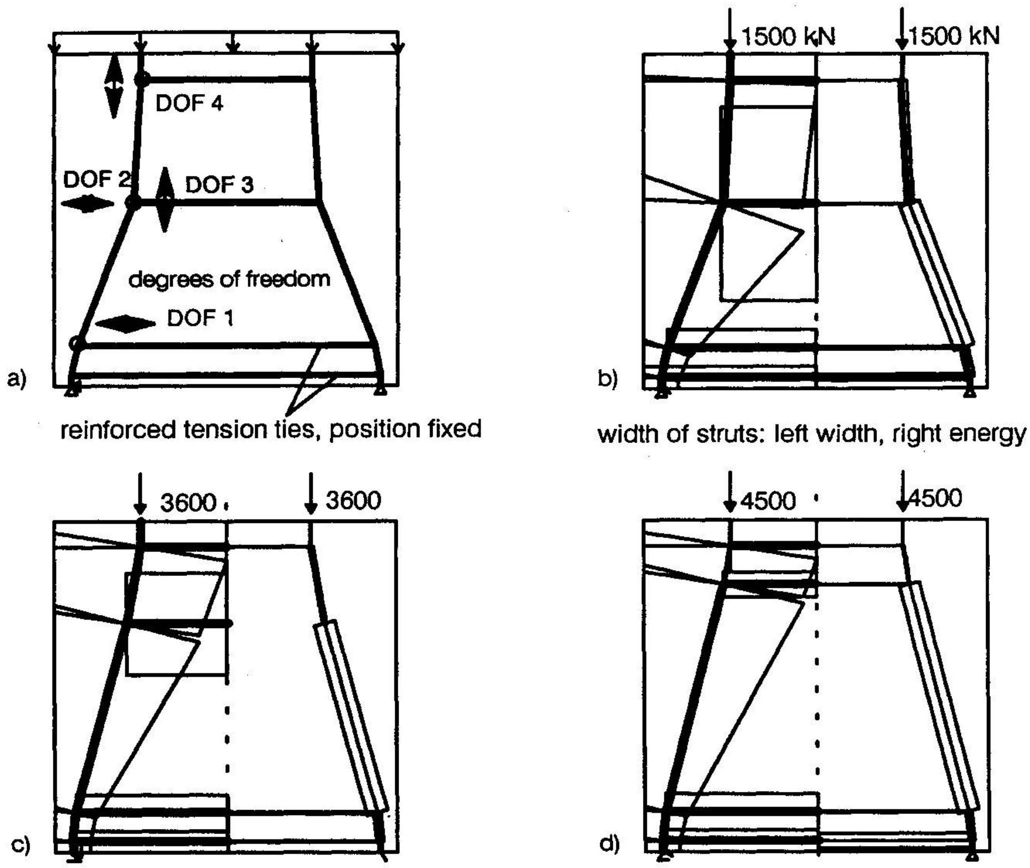

Fig. 7: Adaptation of model under increasing load

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