DESIGN INSTRUMENT SPANCAD FOR SHEAR WALLS AND D-REGIONS

Johan Blaauwendraad Pierre C.J. Hoogenboom

Delft University of Technology
Faculty of Civil Engineering and Geosciences
Delft, The Netherlands
e-mail: J.Blaauwendraad@citg.tudelft.nl

Keywords: reinforced concrete, shear walls, software, stringer-panel model, design procedure

Summary: This paper describes a program for interactive design of shear walls and deep beams of irregular geometry. The software can be used to assemble a design model out of two types of elements, stringers (straight bars) and panels (quadrilaterals). The design procedure consists of three steps. In the first step linear-elastic material behaviour is used. In the second step non-linear material behaviour is used, which allows cracking of concrete and yielding of panel reinforcement. In this step the stringer reinforcement is kept linear-elastic. In the third step a non-linear simulation of the structural behaviour is performed including cracking and crushing of the concrete and yielding and breaking of all reinforcing steel. Thus, the interactive procedure accounts for redistribution of stresses. The result is a final layout of the reinforcement that fulfils conditions on crack widths, deformation and strength. A design example is included.

1 INTRODUCTION

Shear walls and deep beams of complicated geometry frequently occur in civil engineering structures. Design of these elements is a considerable challenge for the responsible structural engineers. Often the element is divided in B-regions and D-regions. Obviously, B-regions are the parts of a structure in which the classic beam theory applies and for which we can think in terms of the familiar bending moments and shear forces (Bending). On this subject we have plenty of knowledge. The remaining part of the structure consists of D-regions in which the fore-mentioned classic state is disturbed (Disturbance). Examples are beam column joints, openings in the web of a beam, dented beam-ends, and so on. A shear wall with irregular shape actually needs to be considered as one large D-region. The software SPanCAD has been developed for design of such D-regions. It runs on a personal computer and is based on AutoCAD for its drafting functions [1].

1.1 Pro's and con's of existing methods

In current design practice two methods are generally accepted, the finite element method and the strut-and-tie method. In the finite element method usually a linear-elastic analysis is performed to obtain the stress distributions for all load cases. Subsequently, a post-processing program can be used to determine the required reinforcement automatically. This method is fast and simple, however, impractical reinforcement layouts may be found and proper detailing of the reinforcement is easily overlooked.

The important advantage of the strut-and-tie method is its simplicity and transparency. The engineer is aware of the force flow and details can be designed safely. However, a different strut-and-tie model needs to be made for every load case. Moreover, in statically undetermined models several different strut-and-tie model might be drafted per load combination and one can run into debates with certifying authorities

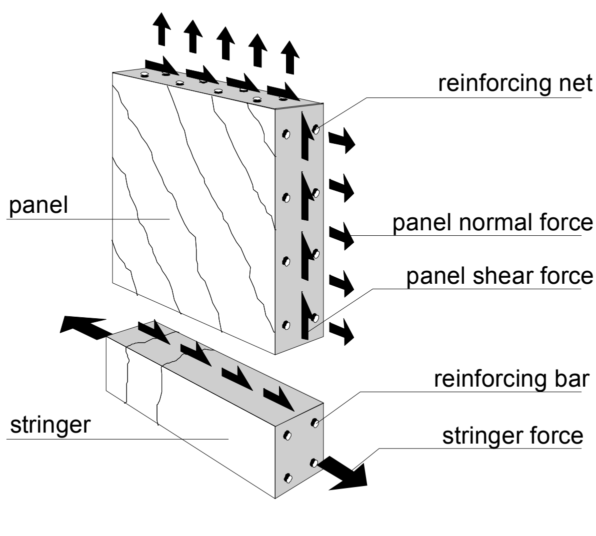


Fig. 1 Stringer and panel elements

as to which one should be selected. Also crack control in the serviceability limit state is not covered. Inexperienced structural engineers, who intend to apply the strut-and-tie method, start making a linear-elastic finite element analysis to understand the force flow from the directions of the principal stresses. Many structural engineers apply a truss program to determine the forces in a strut-and-tie model. When the real stiffnesses of struts and ties are taken into account the model can be statically indeterminate and displacements can be interpreted.

1.2 An alternative: SPanCAD

This introduction brings us naturally to the program SPanCAD. The aim of this new software is to offer an alternative design tool, which combines a number of advantages and releases a number of drawbacks. It aims for:

- applicable in an early stage of the design process,
- PC environment, under Windows, ready while you wait,
- the same model for elastic state and failure state,
- the same model for different load combinations,
- for shear walls, deep beams and cellular structures,
- information about crack-widths and displacements,
- interactive design tool; the engineer is on the lead.

The program SPanCAD is based on a special type of element method. In the standard finite element method it is practice to apply a mesh as fine as possible, but SPanCAD is developed to apply the coarsest mesh for a given geometry. This has been obtained by feeding much concrete mechanics intelligence into the elements. The second special feature of SPanCAD is the type of elements. Only two types exist, a stringer element (straight bar) and a panel element (rectangle or quadrilateral). This resulted from observation of several structural designs for shear walls and D-regions in beams. It was noticed that main reinforcement often occurs concentrated at the edges and around holes (tensile stringers in SPanCAD). Between those stringers wall parts occur in which distributed net reinforcement is applied (panels in SPanCAD).

This paper will focus on the potential of SPanCAD. The non-linear characteristics of the stringers and panels are shown in Figure 2. The stringer behaviour is based on the Eurocode and the panel behaviour on the modified compression field theory as has been developed at the University of Toronto [3]. For the detailed theory and experimental verification we refer to publications [4][5].

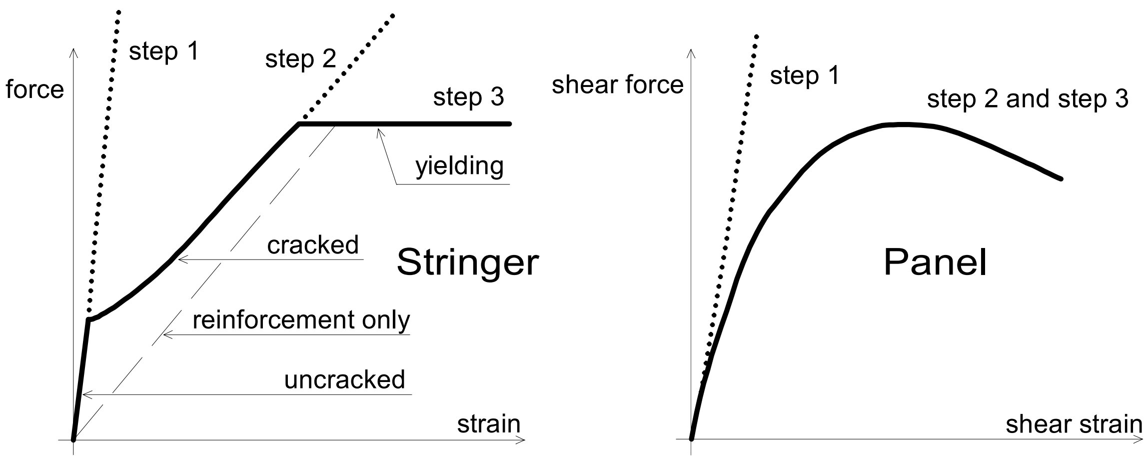


Fig. 2 Non-linear constitutive behaviour of stringers and panels in SPanCAD

2 A THREE-STEP DESIGN PROCEDURE

2.1 First step, elastic analysis

A structural design is made in three steps. In the first one a linear-elastic model is used. In this step the stringer-panel model carries all normal forces in the stringers only and carries all shear forces in the panels. The model is a perfect equilibrium system in which the panels carry constant shear and the normal forces in the stringers vary linearly. In this first step the force flow is not much influenced by the sizes of cross-sections assigned to the stringers. The structural engineer makes rough estimates using experience and rules of thumb. All panels have the same thickness as the wall. The software performs the linear-elastic analysis for all load combinations. The force distribution obtained in this way will be used in the next step to select reinforcement.

2.2 Second step, non-linear analysis

In the second step the structural engineer selects reinforcement based on force flow computed before. In compressed stringers the cross-section area is derived from compression zone (stress block) that can be expected. In tensioned stringers the cross-section area depends on the position and diameter of the bars. It is important to calculate this area accurately because it determines the tension-stiffening of the stringer, which is not only important for the deflections but for crack widths as well.

All input quantities being determined and entered into the program, the software performs a non-linear analysis. The model used accounts for concrete cracking in the tensioned stringers and panels. The reinforcement of the stringers is kept linear-elastic but the panel reinforcement can yield. The latter has advantages for making design improvements in the third step. In step 2 the stress state in the panels is extended to shear and normal stresses.

A non-linear analysis is successively made for each load combination. The load is controlled by a load factor that starts at zero and is increased in small increments until 1 at which the full load combination is at the model. The structural engineer can follow the progress of the analysis on the screen where a load-displacement graph is being drawn. Obviously, this graph will not be linear due to cracking and yielding.

As mentioned before, in this step SPanCAD does not allow yielding of the main reinforcement in the stringers. In case a stringer force would reach the tensile yield strength SPanCAD artificially extends the cracked branch in the force-strain diagram of the stringer (Figure 2). The analysis results show whether or not the ultimate tensile strength of a stringer has been exceeded for any of the load combinations. SPanCAD also shows the crack-widths at service loads. Due to redistribution of stresses and the extended capacity of the panels in this second step it may also occur that the reinforcement in a tensioned stringer can be reduced.

2.3 Third step, simulation

The structural engineer improves the reinforcement using the just computed force flow and crack widths. Normal dimensioning formulae can be used available in codes of practise. Subsequently, SPanCAD performs a simulation for each load combination. In the simulation no restrictions are imposed on the non-linear response of the model. If everything goes well the result of these computations will satisfy the performance criteria and the design is completed. If the structural engineer is not content with some part of the design he or she can do a new step 2 or directly do a new final step 3 for further improvement.

It has been shown that SPanCAD, if applied in this way, is a robust and fast program. The linear-elastic analysis is done more or less instantaneously and the non-linear analysis and final simulation only require a couple of minutes on a PC. In fact the time involved with the initial modelling of the structure and the professional decisions made by the engineer are determining for the duration of the design process.

The final work to do is detailing. Particular attention must be paid to the anchoring of the main reinforcement. At free edges the stringer force will be zero suggesting that hooks or T-ends are not needed. This is not always appropriate and often bars need to be extended to the free edges and anchored carefully.

2.4 Classical cases covered

SPanCAD has been designed for complicated D-regions but it also shows the right behaviour when applied to the familiar B-regions. As an example Figure 3 shows a simply supported statically determinate deep beam. The horizontal stringers at the top and bottom carry the bending moment (compression zone and tension zone). The panels in the web between the stringers carry the shear force. Vertical stringers introduce the loading and support reactions into the beam.

If the main reinforcement in the bottom stringer yields first, the structure will fail in bending. If the stirrups yield first, the beam will fail in shear. In both cases ultimate loads predicted by the model agree well with experimental ultimate loads. SPanCAD produces inclined principal compressive stresses that are in good agreement with the predictions from the classical plasticity theory [6], [7].

Shear is also dominant in cellular structures under torsion loading. Figure 4 shows an example of such a structure. Again, SPanCAD produces inclined cracks in accordance with plasticity theory for torsion in structural concrete. Both the longitudinal reinforcement in the stringers and the transverse reinforcement in the panels are tensioned. The tension in the stringers is caused by dilatation of the panels.

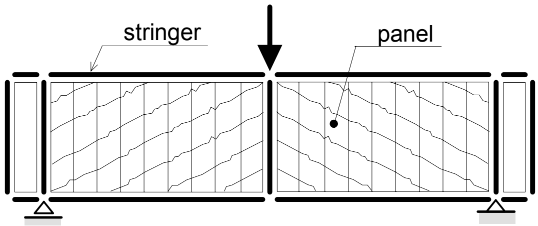


Fig. 3 Simply supported beam model

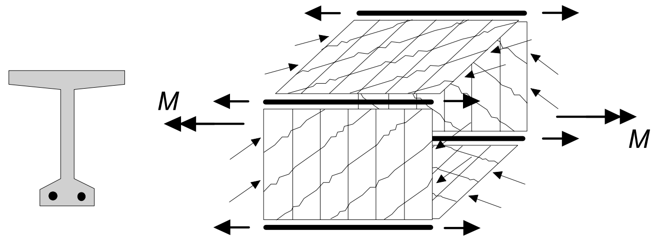


Fig. 4 Box-girder beam model

3 DESIGN EXAMPLE

The deep beam of this example is simply supported and has a large opening (see Figure 5). The stringer-panel model of this beam is shown in Figure 6. Only two independent concentrated forces F_1 and F_2 act on the beam. Other load cases such as dead load or thermal load are neglected for concision of the example. As presented in Table 1, the loading for the service limit state consists of 3 load combinations. The loading for the ultimate limit state consists of 4 combinations. The material properties of the deep beam are assembled in Table 2. The material safety factors of the ultimate limit state are 1.15 for the yield strength of reinforcement and 1.2 for the compressive strength of concrete.

Table 1 Load combinations and performance criteria of the limit states

		Load Combinations	Performance Criteria
Serviceability Limit State	1	F_1	Crack width < 0.4 mm
	2	F_2	Displacement < 20 mm
	3	F_1 & F_2	
Ultimate Limit State	4	1.3 F_1	No collapse
	5	1.4 F_2	
	6	0.9 F_1 & 1.2 F_2	
	7	1.2 F_1 & F_2	

Table 2 Material properties of the deep beam

Concrete		Steel Reinforcement	
Compressive Strength	- 40 MPa	Yield Strength	500 MPa
Young's Modulus	36000 MPa	Young's Modulus	200000 MPa
Tensile Strength	2.4 MPa	Hardening Modulus	0 MPa
Ultimate Strain	- 0.0035	Ultimate Strain	0.06

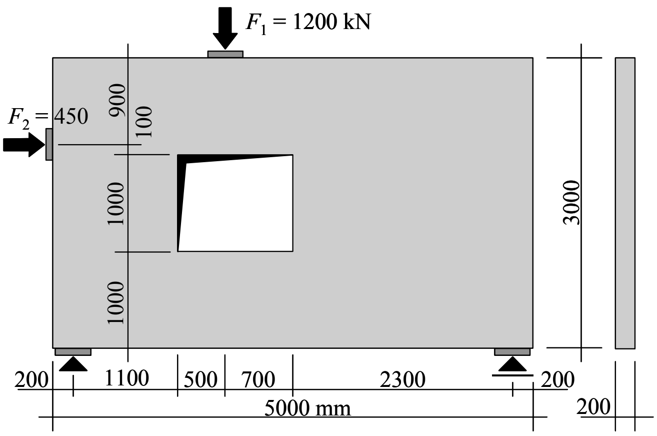


Fig. 5 Deep beam with opening

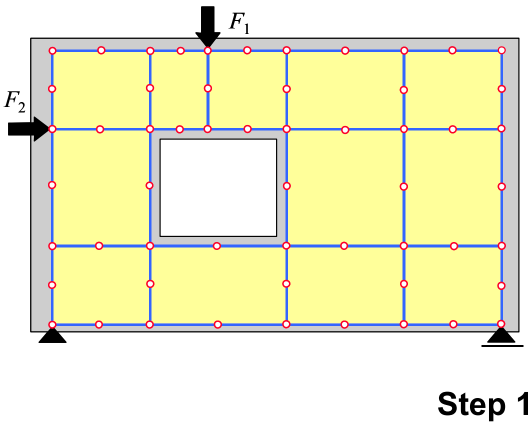
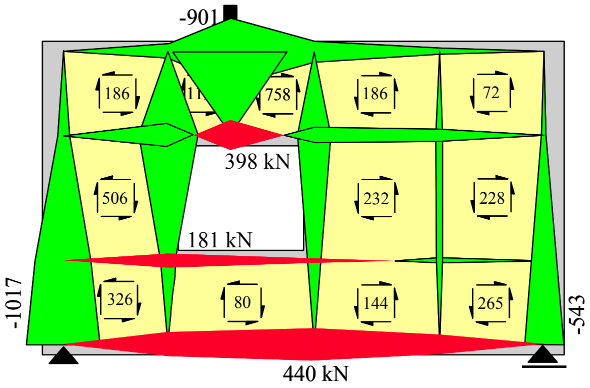


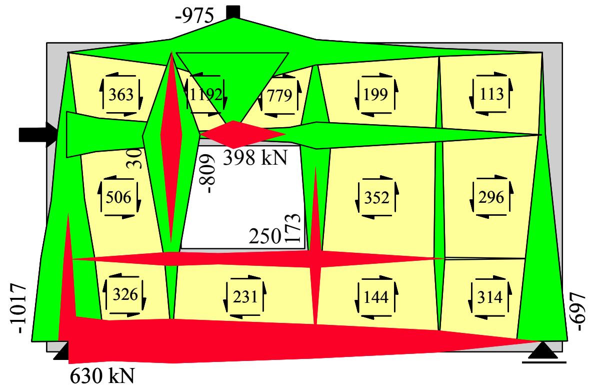
Fig. 6 Stringer-panel model of the deep beam in Figure 5

Figure 7 shows the force flow in the linear-elastic stringer-panel model for load combination 4. Figure 8 shows the envelope of the stringer and panel forces for all load combinations of the ultimate limit state. This figure is used to select initial reinforcement for the beam and concrete cross-section areas for the stringers (Figure 9). At both surfaces a standard net is placed of 7 mm bars with 200 mm spacing in horizontal and vertical direction. This provides a reinforcement ratio of 0.0019. In the panels with large shear forces, additional stirrups are placed. Often, stringer reinforcement is extended to the edges of the wall to include sufficient anchorage or prevent large cracks at bar tips. The size of the concrete section area of tensioned stringers is selected to represent tension-stiffening. The concrete section area of the compressed stringers represents the compression zone of the stress blocks.



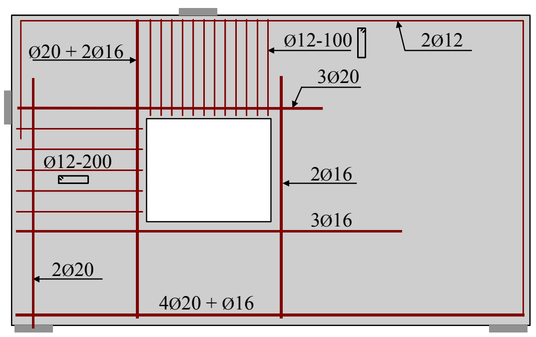
Step 1

Fig. 7 Force flow in the linear stringer-panel model for load combination 4. Tension in a stringer is plotted red, while compression is green.[1] Stringer forces have the unit kN and panel shear flows are in kN/m.



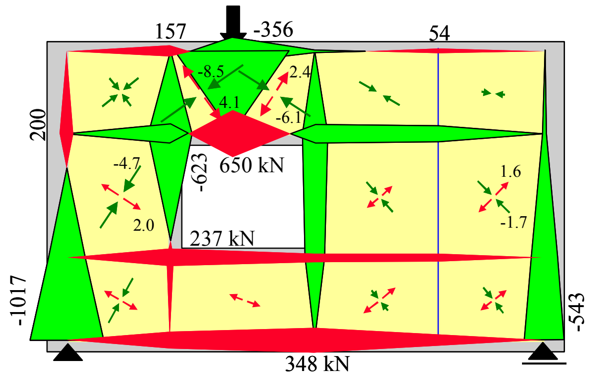
Step 1

Fig. 8 Envelope of the stringer and panel forces for the load combinations of the ultimate limit state



Step 2

Fig. 9 Reinforcement based on the force flow in Figure 8. In addition, over the whole surface a standard net is present of 7Ø-200.
(95 kg panel reinforcement and 125 kg stringer reinforcement. Detailing reinforcement is not included.)



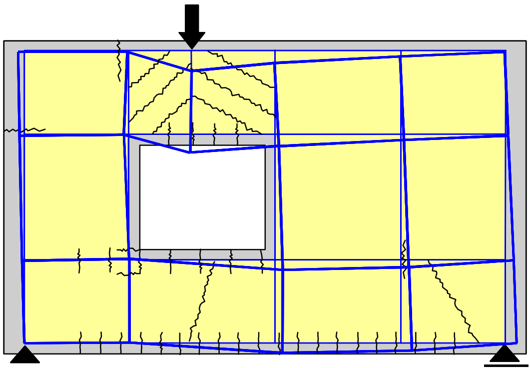
Step 2

Fig. 10 Nonlinear force flow for load combination 4. Substantial redistributions occur in comparison with Figure 4. The principal stresses in the panels have the unit N/mm².

Subsequently, the nonlinear analysis is performed. Most of the cracks are sufficiently small for the load combinations of the service limit state. However, the panel below the opening has a large crack of 0.8 mm width. This shows that the reinforcement below the opening needs to be better distributed. Also some cracks at the top edge of the beam become rather wide. This is caused by a substantial redistribution of the force flow. Figure 10 shows this force flow for load combination 4. Some stringers that were compressed in the linear model are tensioned in the nonlinear model. This can be understood from the deformations in Figure 11. The part above the opening appears to push the left part of the beam outwards.

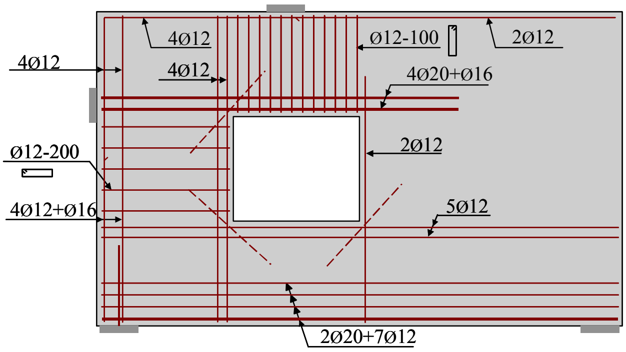
[1] If this paper is printed without colour the stringer forces will show as dark grey and grey for tension and compression respectively.

The reinforcement is redesigned according to Figure 12. Though reinforcement is selected economically, it is not attempted to use redistributions from the load carrying system of one load combination to another. Finally, simulations of the beam behaviour for all load combinations show that service and ultimate limit states do not occur. Figure 13 shows the behaviour of the beam for load combination 4. In this graph, the vertical axis displays the load factor and the horizontal axis the displacement of the point at which the force F_1 acts.



Step 2

Fig. 11 Deformed stringer-panel model and cracks of load combination 4. Of course, the deformations are plotted exaggeratedly. The largest displacement is only 3.3 mm.

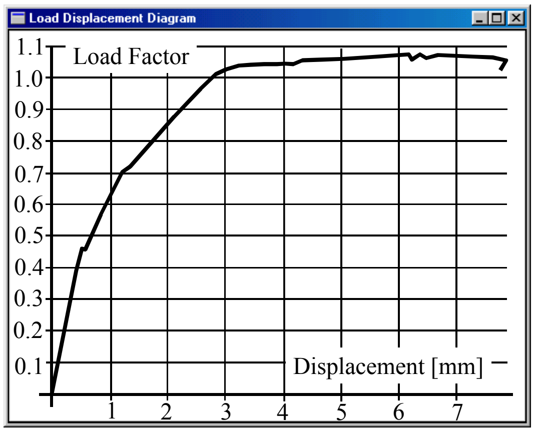


Step 3

Fig. 12 Redesigned reinforcement in the deep beam (115 kg panel reinforcement and 130 kg stringer reinforcement. Detailing reinforcement is not included.)

The full load combination acts on the model at a load factor of 1. The strength of the beam shows to be somewhat more than required and its ductility is sufficient. For the other load combinations of the ultimate limit state, the model shows an ultimate load factor between 0.98 and 1.18.

Detailing of the reinforcement is clearly equally important, but not included in this example. Especially, the left-hand support should be designed carefully because it may be tensioned in both directions. Sound anchoring of reinforcement is a subject of concern here. Also it may be prudent to provide inclined bars at the corners of the opening to disperse cracking. This reinforcement is drawn with the dashed lines in Figure 12.



Step 3

Fig. 13 Load displacement curve of the simulated behaviour for load combination 4

REFERENCES

[1] AutoCAD (Software), Autodesk Corporation, Version 13 for PCs c4a, Online (July 23, 1998) http://www.autodesk.com/, San Francisco.
[2] Eurocode, “Common Unified Rules for Concrete Structures”, ENV1992-1-1:1991, pp. 171-174.
[3] Vecchio F.J., M.P. Collins, “The Modified Compression-Field Theory for Reinforced Concrete Elements Subjected to Shear”, ACI Journal, Vol. 83, No. 2, March-April 1986, pp. 219-231.
[4] Blaauwendraad, J., P.C.J. Hoogenboom, “Stringer Panel Model for Structural Concrete Design”, ACI Structural Journal, Vol. 93, No. 3, May-June 1996, pp. 295-305.
[5] Hoogenboom, P.C.J., “Discrete Elements and Nonlinearity in Design of Structural Concrete Walls”, doctoral thesis, Delft University of Technology, 1998.
[6] Bræstrup, M.W., M.P. Nielsen and F. Bach, “Rational Analysis and Design of Stirrups in Reinforced Concrete Beams”, Technical University of Denmark, Structural Research Laboratory, Report R 79, March 1977.
[7] Nielsen, M.P., “Limit Analysis and Concrete Plasticity”, ISBN 0 13 536623 2, Prentice-Hall, London, 1984.