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Evolutionary structural optimization as tool in finding strut-and-tie-models for designing reinforced concrete deep beam

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Abstract

Strut-and-Tie models are well-known worldwide as valuable tool in designing D-Regions of Reinforced Concrete members. It has been adopted in many Concrete Structural Codes in many countries. Recently strut-and-tie-models have been included in Indonesia Concrete Structural Code (SNI-03-2847-2012). In this paper, it will be shown how a Strut-and-Tie Model can be developed for various structural concrete deep beams using Evolutionary Structural Optimization. As a tool for this study the author used Bi-Directional Evolutionary Structural Optimization (BESO2D) computer programs, developed by X. Huang and Y.M. Xie [1]. Three tested concrete beams with small, medium, and large opening [2] will be taken as the case study. It will be shown the optimal topology of a plane stress of continuum structures produced from BESO2D can be taken as the basic strut-and-tie-model. For design process the best strut-and-tie-model can be delivered from the optimal topology structure only with the deep knowledge of the basic load transfer from loading to support point

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1. Introduction

Strut-and-tie models are conceptual tools for design of reinforced concrete structure. It is considered the basic tool in the design of reinforced concrete structure members under the loading. Actually Strut and Tie Model was conceived by Ritter [3,4] and was developed by Mörsch [3,4], introduced it as Truss Analogy.

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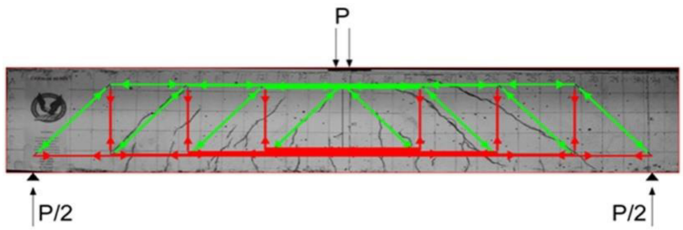

Fig.1. Mörsch Truss Analogy for cracked concrete beam.

Since 1980, Schlaich, et al. [3,4] investigated this truss analogy to be consistent design approach for the design and detailing of structural concrete and named it *Stabwerkmodell* (Germany), which is now called strut-and-tie-model. It allows any part of the concrete structure to be designed by using strut-and-tie-models. The model is based by the fact that the loads are carried by the cracked concrete structure through a set of compressive stress (STRUT) and tensile stress (TIE).

The strut-and-tie-models assume that all stresses condense in compression and tension members and join them by nodes, likely in truss structure. Based on this technique, finding an optimal strut-and-tie-model in the concrete structure member is a main task for the structural engineer. Schlaich, et al. [3,4] had proposed the basic technique to find appropriate strut-and-tie-model by using the elastic stress distribution and load paths method.

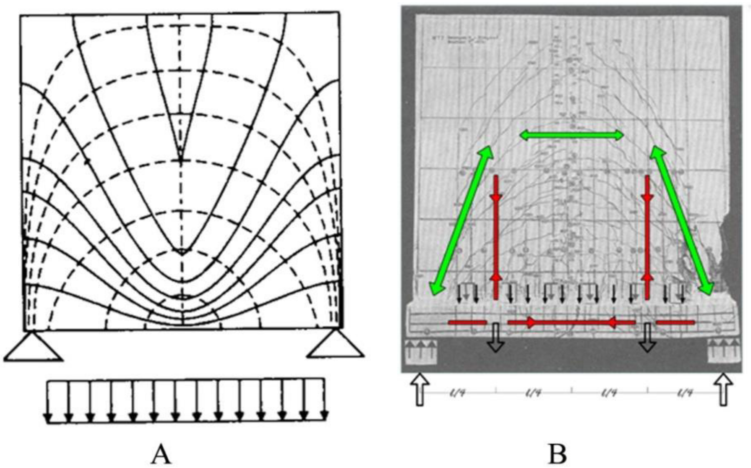

Fig.2. A. Principle stress trajectories of wall structure with distributed load.
B. Cracked concrete wall and its strut-and-tie-model [3,4].

In this approach, the strut and tie model is formed by orientating the struts and ties to the principle stress trajectories, which can give the imaging of load transfer mechanism in the cracked concrete structure member from the point of the load (action) to the structure support (reaction). It is difficult and time consuming, however, to find the good model in structure members with complex load and geometry conditions using the load paths technique. These obstacles can be reduced if we use evolutionary structural optimization as a tool in finding strut-and-tie Model. Structure like a truss can be created by using this technique. In [5] the author had shown that the load paths technique and the structure topology generated from evolutionary structural optimization could complement each other in finding the best strut-and-tie-model.

In this paper the author will present the study of finding the appropriate strut-and-tie models with helping a computer based program of Evolutionary Structure Optimization, named BESO2D (Bi-Directional Evolutionary Structural Optimization) developed by Huang and Xie [3]. Three tested concrete beams with small, medium, and large opening [2] will be analyzed by using BESO2D. The truss model which generated from BESO2D will be compared with the Strut-and-Tie Models, which were used for determining their shear reinforcement.

2. Practical Application of Computer Program BESO2D

BESO2D is a software for evolutionary structural optimization [6]. This method is developed based on material removal criteria. The defined performance indexes are used to monitor the optimization process, and also to measure the performance of structural topologies. The computer program BESO2D produces the optimal topology of a plane stress continuum structure, which is normally "Truss-Like Structure". These topology shapes were interpreted as the appropriate Strut and Models in structural concrete. Liang, et al. [7] used this technique automatically in finding the appropriate strut-and-tie model in reinforced concrete structure.

The key process of evolutionary structural optimization in computer program BESO2D can be outlined as following:

- Removing inefficient materials in carrying the load from the structure, with the condition that the minimizing the weight of the structure can be achieved while the deformation can be kept within certain limit.
- Element Removal criteria based on displacement formulation. Only elements with the lowest sensitivity in the constrained deformation can be removed.
- In processing of topology optimization, the cycle of finite element analysis and element removal is repeated and the performance of the resulting structure is step by step improved.
- The accuracy of the solution is improved by adopting a smaller Element Removal Ratio (ERR). To have reasonable solution ERR should be taken 1 % or 2 %.

Picture 3 shows as an example a cantilever beam loaded with Point Load F analyzed with BESO2D to find its optimal topology of a plane stress continuum structure. After the removal inefficient materials achieved 65%, the topology of a plane stress continuum structure can be treated as a Truss like structure. See figure 3C.

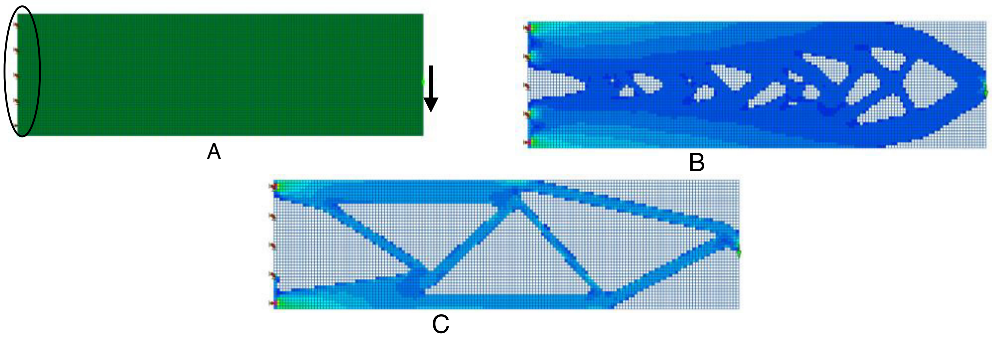

Fig.3.A. A finite element mesh of cantilever beam structural model with support and point load.
B. Intermediate design during optimization process with 80% volume fraction.
C. Final optimization process with 35 % volume fraction.

3. Strut-and-Tie-Models for the Beams with Small, Medium and Large Opening.

In [2] the author reported result of the loading test of three beams with small, medium and large opening. Due to the opening, in fact all the beam areas are grouped as D regions, where hypothesis of Bernoulli cannot be applied. It can be concluded that the beams can be treated as deep beams. In determining the shear reinforcement the author had analyzed all the beams based on the modified truss analogy and followed load path technique in finding the appropriate Strut-and-Tie Model, as can be seen in figure 4.

In many cases, developing an appropriate strut-and-tie model for a complex concrete member is perhaps the most difficult task in the design process. Afterwards, dimensioning the truss model is straightforward according to codes of practice and is not the objective of this paper. To speed up and ease the design process, the author will demonstrate using evolutionary structural optimization as a tool in finding the best Strut-and-Tie Model for these three beams with opening. For that purpose a computer based program of Evolutionary Structure Optimization (BESO2D) will be applied to analyze them in two steps.

First step is modeling finite element mesh for each beam with boundary and loading condition. Second step is processing of topology optimization, done automatically. Finally, we can choose percentage of volume fraction, which will give us the appropriate model for strut-and-tie-model. The optimal topology structure shown in Figure 5 (A, B, C) indicates a structure like truss, which can be seen as best layout of the strut-and-tie model for each beam with opening.

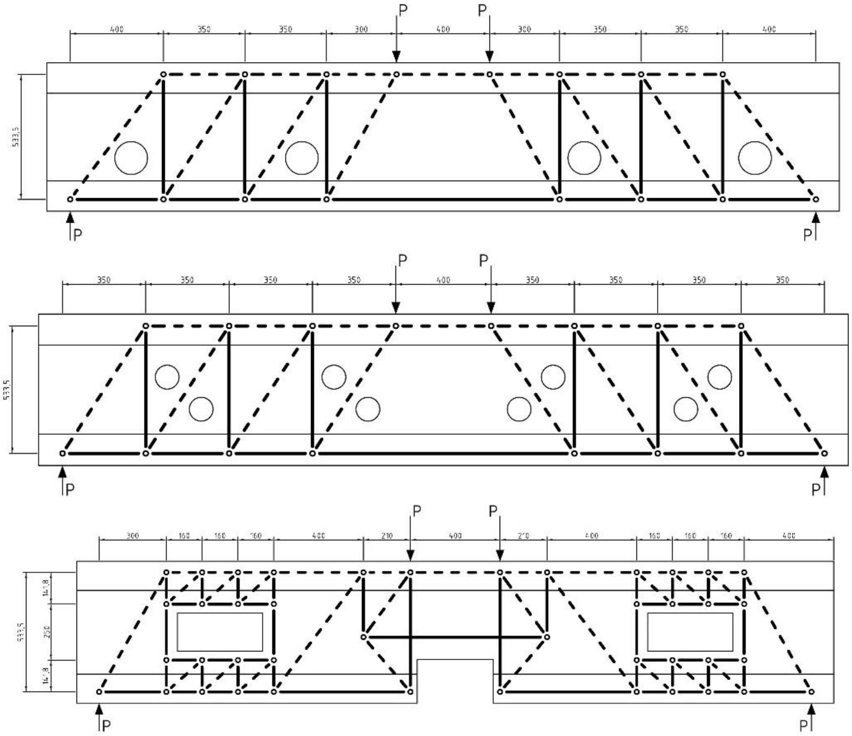

Fig.4. Strut-and-tie-model for beam with small (Beam A), medium (Beam B) and large (Beam C) opening according to [2].

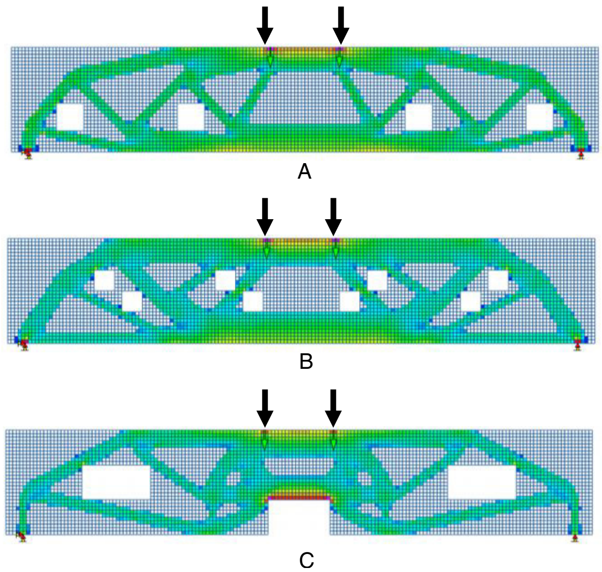

Fig.5. A. The final optimal topology of beam A (small opening) with 50 % volume fraction.
B. The final optimal topology of beam B (medium opening) with 60 % volume fraction.
C. The final optimal topology of beam C (large opening) with 50 % volume fraction

According to this optimal topology of each beam in Figure 5 the strut-and-ties can be accurately located, by positioning the compression and tension members in this structure like truss. It means that the optimal topology shown in Figure 5 is idealized as the strut-and-tie model shown in Figure 6, which can be used to determine the internal forces of the truss and reinforcement arrangements in the detail design.

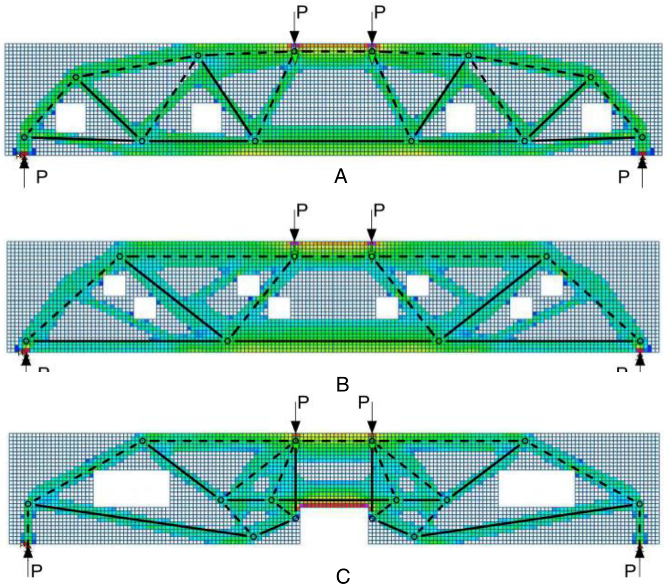

Fig.6. Strut-and-tie-model of beam A, B, and C.

4. Conclusion

Strut-and-tie-model is considered as the basic tool in the design of reinforced concrete structure on a wide variety of D zones. Although Strut-and-tie-models have been included in the Indonesian National Standard SNI 2847-2013 recently, but in fact the design process still has barriers to find appropriate strut-and-tie-model. Therefore this paper is aimed to improve and ease design process in finding strut-and-tie-model by using evolutionary structural optimization technique.

A computer program BESO2D for executing evolutionary structural optimization has been applied on three simple beams with small, medium and large opening. Based on the strut-and-tie-model resulted from evolutionary structural optimization the following conclusions can be drawn:

- Computer program BESO2D can speed up and ease the design process in finding strut-and-tie-model, especially in the case of complicated D-beam, like the beam with large opening.
- The strut-and-tie-model from the optimal topology generated from BESO2D can deliver better model rather than strut-and-tie-model generated from simple truss analogy as can be seen in Figure 4.
- It should be that the loads are transferred along shortest natural load paths from the loading to support points. This is confirmed by the strut-and-tie-model in Figure 6 developed from optimal topology resulted from BESO2D. Strut-and-tie model shown in Figure 6 indicates that the loads are transmitted to the supports by the struts in arch action and inclined ties.
- It has been shown in Figure 6 (C), that a complicated structure topology can be modified to deliver simpler STM, by arranging or deleting some parts of topology member.

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