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A computer-based tool for strut-and-tie model design of structural concrete

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Abstract. The strut-and-tie model (STM) method has been recognized as an efficient methodology for the design of structural concrete disturbed stress regions (D-regions) and is used in design codes worldwide. However, the method requires iterative solution, numerous graphical calculations, and is time consuming. Further it involves designer's experience in the development of appropriate STM. In this study, a computer graphics program that enables the analysis and design of structural concrete efficiently is presented. This graphics program enables the designer to overcome the implementation drawbacks mentioned above. The program incorporates analysis and design capabilities, including finite element linear/nonlinear analysis programs for the plane truss and solid problems, a module for the automatic determination of effective strengths of struts and nodal zones, and one for the graphical verification of appropriateness of STM by displaying various geometrical shapes of struts and nodal zones.

Keywords: D-region; Strut-and-Tie Model; computer graphics; structural concrete

1. Introduction

For the ultimate strength design of structural concrete with geometric or static discontinuities, often the use of empirical approaches (applicable to limited and specific design parameters) or complicated numerical methods is necessary. Another challenge is the translation of outputs from these approaches into practical reinforcement detailing. Strut-and-tie models offer an alternate design methodology to aid engineers in the design and detailing of these regions of discontinuity. In the STM method, a D-region or whole structural member with D-regions is modeled as a strut-and-tie system consisting of struts, ties, and nodal zones. The compressive forces in concrete and reinforcing bars are represented by struts, whereas ties represent the tensile forces in reinforcing bars. The regions where struts and ties meet are modeled as nodal zones. The STM also facilitates a better understanding of load transfer mechanisms and structural behavior and improves the designers' ability to handle unusual circumstances. These advantages have motivated engineers and code bodies to adopt the method in national design codes (FIB 2010, EC2 2004, AASHTO

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2018, ACI 318 2019).

In the analysis and design of structural concrete using the STM method, computer-based analysis and design tools have been developed to facilitate its use by designers and researchers. Computer graphics programs enabling the implementation of the STM by visualizing the elastic stress trajectories of unreinforced concrete members were developed by Alshegeir and Ramirez (1992) and Mish *et al*. (1995). A Unix system-based computer graphics program 'NL-STM' was developed by Yun (2000). In the program, nonlinear finite element analysis techniques for structural analyses of unreinforced two-dimensional concrete members and STMs were incorporated. The computer graphics program 'CAST' developed by Tjhin and Kuchma (2002) can be used to verify the strength of STM elements (strut, tie, node) using the cross-sectional areas of struts, ties, and nodal zone boundaries of statically determinate STM.

The programs of previous studies, however, need to be expanded through additional functionalities to further empower the designer. These functionalities include capabilities to:

- Account for the effect of reinforcing bars on elastic stress trajectories and to evaluate the cross-sectional areas and forces in struts and ties of statically indeterminate STMs.
- Impose the self-weight of structural members on the finite element models for structural analyses of unreinforced concrete members and strut-and-tie systems in an automated way, and consider various boundary conditions in the structural analyses.
- Evaluate the effective strengths of concrete struts and nodal zones accurately by reflecting the effects of primary design variables, and describe the cross-section of concrete struts as bottle, variable prism, and fan shapes for precise strength verifications of struts and nodal zones.
- Evaluate the nonlinear behavior and ultimate strengths of structural members by investigating the cause of failure and changing phenomena of deflections, strains, and load transfer mechanisms, and perform the verifications of the strengths of nodal zones correctly by replacing the specifications of current design codes on the effective strength of nodal zones that are considered as the most obscure and inaccurate parts of the design codes.
- Enable user-oriented graphics functions for the pre- and post-processors of connected numerical analysis programs.

In this study, a graphics program 'STM-2D' is presented to overcome the limitations and disadvantages of previous programs and enable the design of structural concrete with STMs. The software is developed to run in Windows operating system. The graphical user interface for displaying results of modeling, analysis, and design is another feature in the program. The environment of the graphical user interface is implemented by the HOOPS graphics package (1997), and high efficiency and convenience in STM analysis and design of structural concrete is feasible by the various graphics environment-based functions of the program. In this paper, the necessity and the representative features of the graphics program are illustrated following the design process of the STM method.

2. Strut-and-tie model method

Structural concrete is subdivided into either B- (beam or Bernoulli) or D- (disturbed or discontinuity) regions, as shown in Fig. 1. Those parts of a structure in which the strains over the depth of the section vary linearly are defined as B-regions, and the remaining parts of the structure in which the strains vary nonlinearly due to abrupt geometrical discontinuities or statical discontinuities are defined as D-regions. The structural concrete, including deep beams, brackets

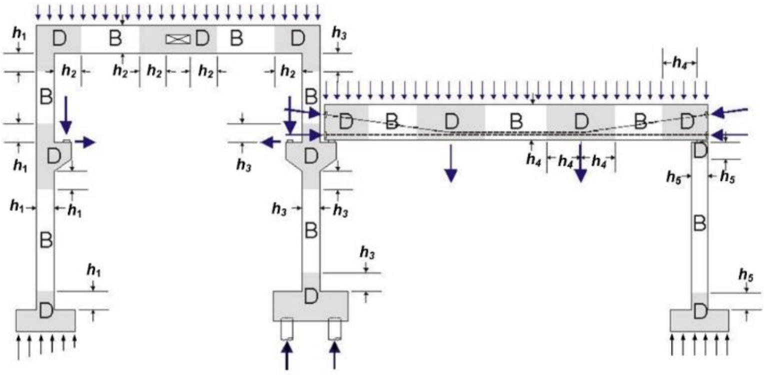


Fig. 1 Examples of B- and D-regions in structural concrete (adapted from Tjhin and Kuchma 2002)

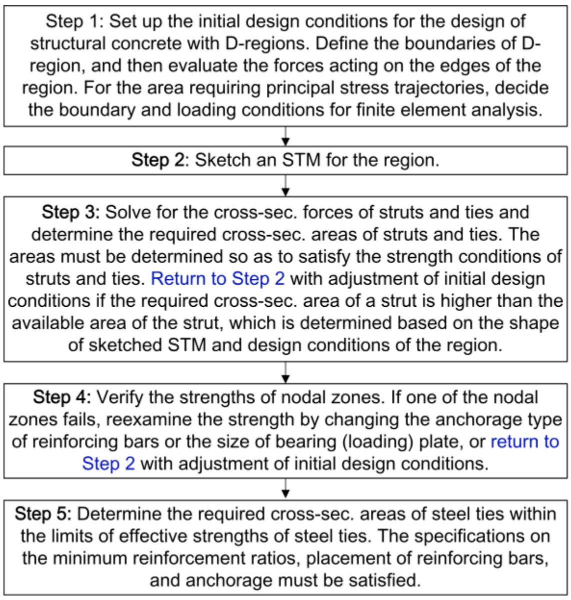


Fig. 2 Design procedure by STM method

and corbels, beam-column joints, dapped-end beam, anchorage zones of prestressed concrete members, and pile caps are representative examples of D-regions (Chetchotisak *et al*. 2017, Özkal and Uysal 2017, Parol *et al*. 2018, MacGregor 2019, Hassoun and Al-Manaseer 2020, Tran *et al*. 2020). The D-regions or structural concrete with D-regions can be designed rationally by the STM method.

The stresses and stress trajectories in the linear elastic uncracked state can be predicted using elastic theory in structural concrete. Although the stresses and stress trajectories after cracking can be estimated using finite element nonlinear analysis adopted in general-purpose commercial programs, it is not practical to employ this approach in design of structural concrete. Due to the complexities associated with this approach owed to the constitutive models for considering material nonlinearities, the finite element models of steel and concrete, the cracking model of

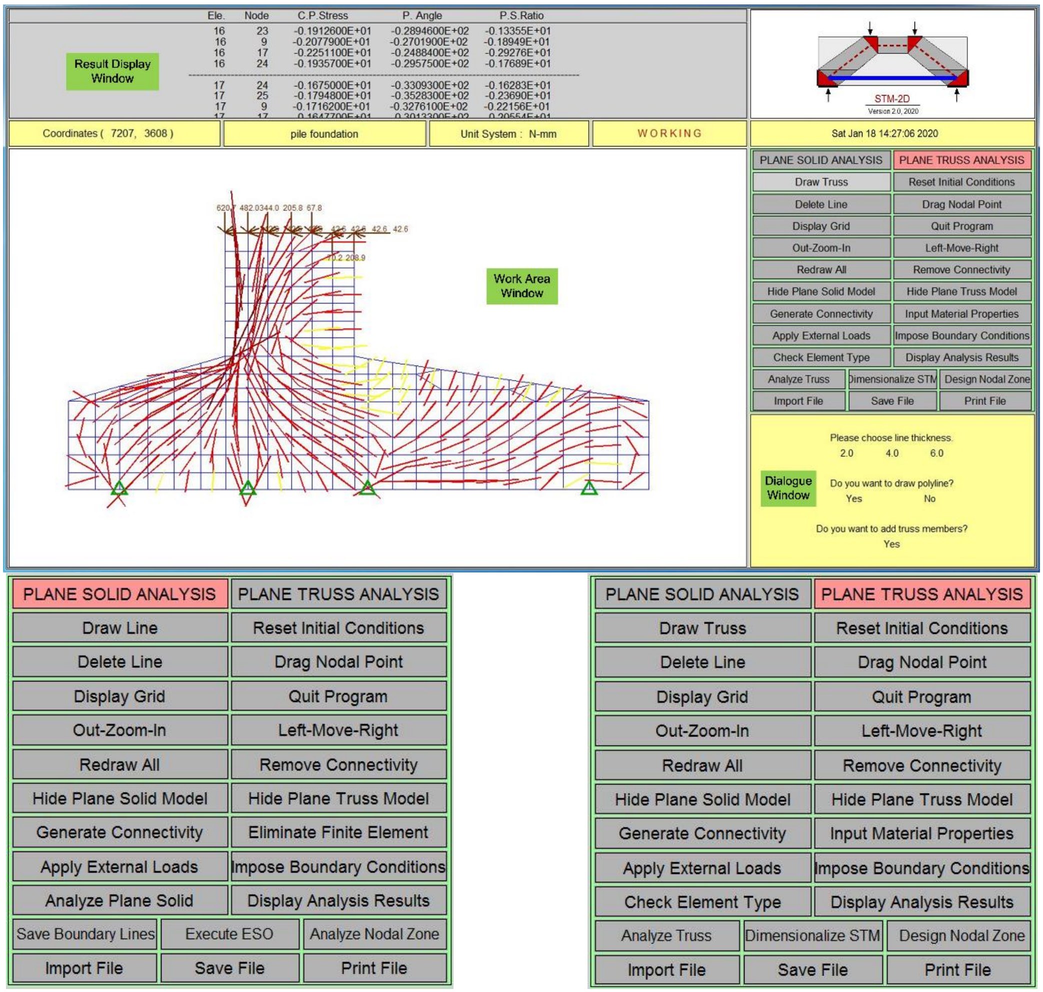


Fig. 3 Window layout and menu systems

concrete, the nonlinear numerical solution techniques, etc., this approach is better suited for assessment rather than design. On the other hand, the redistribution of stresses and load-carrying mechanisms before and after cracking can be followed using the STM method.

The STM design of structural concrete starts by developing an STM for the given design situation. However, as there is not a unique STM associated with a given design, an iterative process is often followed as described in Fig. 2. The graphics program presented in this paper can simplify the iterative process and facilitate the design.

3. Computer graphics program

3.1 Layout of windows

The graphics program of the present study consists of several windows, as shown in Fig. 3.

They are the menu system [PLANE SOLID] window which contains various menus for the pre- and post-process of the finite element linear (nonlinear) analysis of unreinforced plane stress (plane strain, axisymme- tric) structural concrete, the menu system [PLANE TRUSS] window which covers diverse menus for the pre- and post-process of the finite element linear (nonlinear) analysis of two-dimensional truss structure and for implementation of STM design process, and the dialogue window in which a designer enters all the additional information and options for the STM analysis and design of structural concrete. The program also contains the result display window which lists the contents of generated files including finite element analysis results, cross-sectional areas of struts and ties, and effective strengths of struts, ties, and nodal zones, the work area window which enables a designer to make the finite element models of plane solid and truss structures by using graphics user interface functions and shows graphically every types of information following the iterative design process of the STM method, and the coordinate indication window which shows the global coordinates of a cursor in a rectangular coordinate system.

1.2 Determination of principal stress trajectories

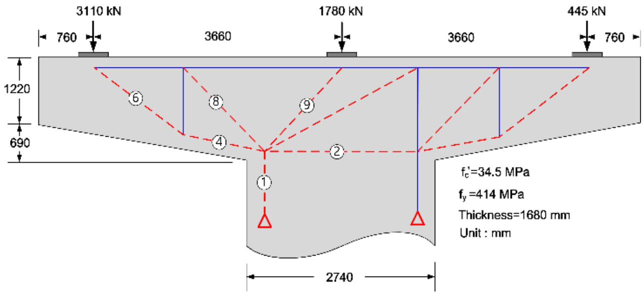
One of the important requisites in the STM method is to develop an appropriate STM by taking account of practical patterns of reinforcement details, constructability, ductility, and serviceability of structural concrete. In many situations, the practicability and easiness of fabrication of structural concrete influence a lot on the development of STM. The development of the model is easy for everyday and straightforward design situations basing a designer’s experience and the load path with visualization of expected failure crack patterns. In more complex design circumstances, the typical engineering sense is not often enough to develop proper STMs. In such cases, the load path method can be supplemented using the principal stress trajectories based on linear elastic analysis of structural concrete (Schlaich *et al*. 1987). According to their method, the compressive principal stress trajectories are used to select the orientation of struts. Then the STM is completed by placing the ties to furnish a stable load-carrying structure.

In this study, the principal stress trajectories of structural concrete are determined by using the plane solid menu system of the present program. The menu system consists of the functions for:

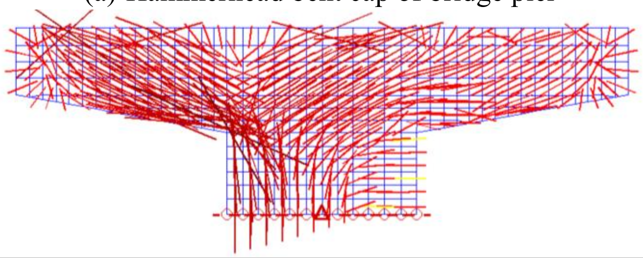
- setting up a working environment,
- drawing and editing a finite element model of plane solid structure,
- automatic numbering of finite elements and nodes,
- remodeling the finite element model of plane solid structure,
- imposing loading and boundary conditions,
- performing a finite element analysis of plane solid structure.

In the function of the working environment, the types of structural concrete (plane stress, plane strain, axisymmetric), the scale of work area using the SI, MKS, and US Customary unit, and the material properties of concrete and steel are reset if necessary. In the functions of drawing and editing, the menus for:

- drawing horizontal, vertical, and random lines,
- deleting existing lines one by one,
- defining the boundary lines of structural concrete,
- enlarging, downsizing, and moving a plane solid model in work area window,
- displaying the finite element numbers, node numbers, and load conditions of plane solid model selectively,



(a) Hammerhead bent cap of bridge pier



(b) Compressive principal stress trajectories

Fig. 4 Compressive principal stress trajectories for hammerhead bent cap of bridge pier

• hiding either the plane solid model or STM,
• displaying the analysis or design results on work area window and result display window,
• supplementing the work area window with grid lines

are involved. In the function of automatic numbering, the menus for automatic numbering of finite elements and nodes with minimizing the array of stiffness matrix, for selecting the plane solid finite element type (4- or 9-node isoparametric) with considering the existence of openings in structural concrete, and for inserting the material properties of plane solid finite elements are provided. In the function of remodeling, the menus for deleting finite elements of plane solid model one by one after constructing element connectivity, for modifying the shape of finite element model by moving the positions of finite element nodes, and for canceling the element connectivity to regenerate a finite element model are included. In the function of imposing load and boundary conditions, the menus for imposing the nodal forces to finite element nodes directly through the dialogue window, for converting the self-weight of structural concrete into the nodal forces automatically, for converting the confinement forces by reinforcing bars into the nodal forces automatically, and for entering various types of boundary conditions (roller, initial displacement, and spring, all with variable angle) are provided.

After completing a finite element model of a plane solid structure by using the above functions and menus of the present program, the structural analysis is carried out. The results of structural analysis, including principal stresses and directions are saved as texts, listed on the result display window, and displayed graphically on the work area window with variable line length and color. The principal compressive stress trajectories determined by the plane solid menu system for the hammerhead bent cap of bridge pier (ACI 445 2010) are shown in Fig. 4. The stress trajectories were obtained with consideration of the effect of concrete confinement by reinforcing bars. For more realistic development of an STM, it is recommended that the finite element analysis results, including the principal stress trajectories, be determined by considering the effect of reinforcing

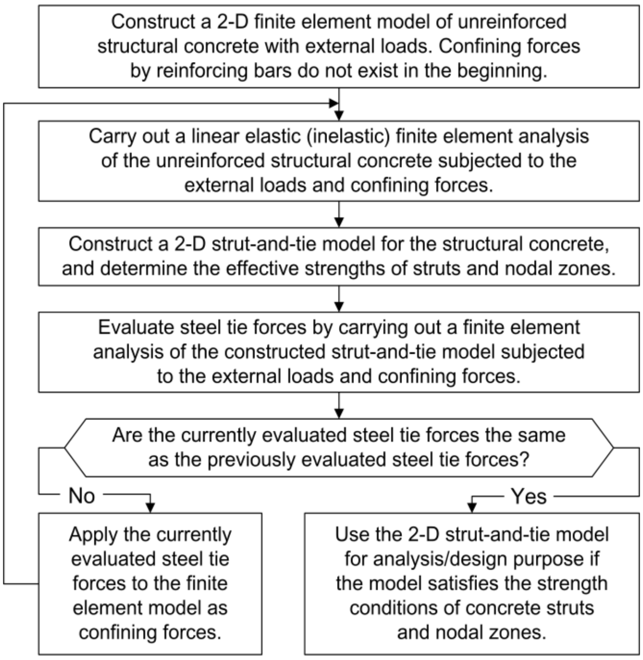


Fig. 5 Algorithm for considering effect of concrete confinement by reinforcing bars

bars. The confinement effect in the present program is reflected by the algorithm shown in Fig. 5.

3.3 Development of STM

In this study, an STM of a structural concrete member (or component) is formed by using the plane truss menu system of the present program. The menu system consists of the functions for setting up a working environment, for drawing and editing an STM, for automatic numbering of struts, ties, and nodes, for remodeling an STM, for imposing loading and boundary conditions, and for performing a finite element analysis of truss structure. As the functions for setting up a working environment, editing, and automatic numbering are similar to those of plane solid menu system the explanations about these functions are omitted.

In the function of drawing an STM, the menus for drawing random lines, for deleting existing lines one by one, and for adding additional lines (struts or ties) after creating element connectivity to make a statically indeterminate STM are provided. In the function of remodeling, the menus for deleting struts or ties one by one after generating element connectivity, for modifying the shape of STM by moving the positions of STM nodes, and for canceling the element connectivity to regenerate an STM are associated. In the function of imposing load and boundary conditions, the menus for:

• imposing the nodal forces to STM nodes directly through the dialogue window,
• converting the self-weight of structural concrete into the nodal forces automatically,
• converting the confinement forces by steel ties (reinforcing bars) into the nodal forces automatically,
• entering various types of boundary conditions (roller, initial displacement, and spring, all with variable angle)

are provided. With the above functions and menus, special types of STMs, such as statically indeterminate STMs and models that have multiple struts (concrete strut, steel strut) or multiple ties (steel tie, concrete tie) sharing the same nodes at their ends, can be constructed.

3.4 Evolutionary structural optimization

When a technique incorporating the elastic stress trajectories is employed for the development of STM, different design models may be developed with equilibrium as the requirement. A given STM may follow the designer's experience and subjectivity. Hence, the reliability of the design can be impacted by deficient understanding the structural behavior and load transfer mechanism (Zhong *et al*. 2017, Yun *et al*. 2018, Xia *et al*. 2020). To overcome the shortcoming, the proposed program looks for the optimized load transfer mechanism by an evolutionary structural optimization (ESO) technique (Liang *et al*. 2002). In ESO, a given member (or subassembly) is modeled with finite elements. The finite elements that are not playing important roles are eliminated gradually through iterative structural analysis to find an optimized shape. Three and four-node plane stress, plane strain, and axisymmetric isoparametric elements are used in the program. For the gradual elimination of finite elements, the conditional equations shown in Eq. (1) associated with the Von Mises stresses (σ_e^{VM}, Eq. (2)) and the strain energy (W_e, Eq. (3)) were applied. The optimum shape is determined when the performance index (P_{index}, Eq. (4)) becomes a maximum value. The program stops automatically when the performance index is less than 1.0, or the structure composed of remaining finite elements becomes unstable.

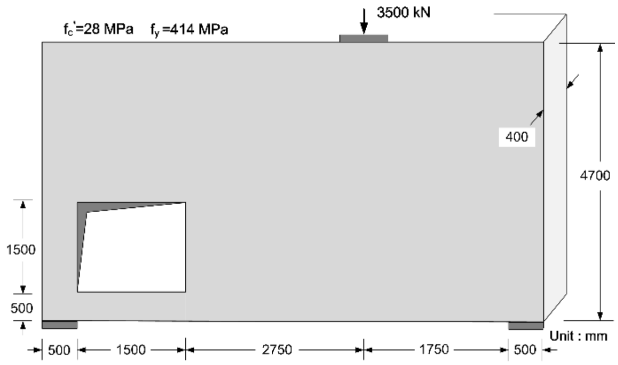
$$\sigma_e^{VM} \le \sigma_{\max}^{VM} \times RR; \quad W_e \le W_{\max} \times RR \tag{1}$$

$$\sigma_e^{VM} = \sqrt{\frac{1}{6}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \tag{2}$$

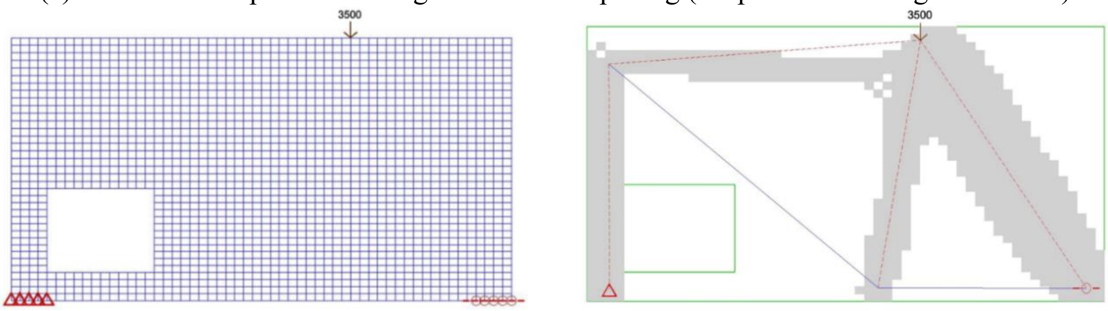
$$\begin{aligned} W_e = {} & \frac{1-2\nu}{6E}(\sigma_1 + \sigma_2 + \sigma_3)^2 \\ & + \frac{1+\nu}{6E}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \end{aligned} \tag{3}$$

$$P_{index} = \frac{E_o W_o}{E_i W_i} \tag{4}$$

In the above equations, σ_e^{VM} and W_e are the Von Mises stress and strain energy of finite element e; $\sigma_{\max}^{VM}$ and $W_{\max}$ are the maximum values of Von Mises stress and strain energy among all finite elements; RR is the elimination ratio; σ_i (i=1,2,3) is the principal stress of finite element, v is the Poisson's ratio; E_o is the strain energy of a structure before elimination; E_i is the strain energy of a structure composed of remained finite elements at elimination step i; W_o is the weight of a structure before elimination; and W_i is the weight of a structure at elimination step i. An example of evolutionary structural optimization for the transfer girder with an opening is shown in Fig. 6. In the process of optimization an elimination ratio of 0.01 and 1072 four-node isoparametric plane stress finite elements were used. Seventy-four percent of finite elements were eliminated when the performance index became less than 1.0.



(a) Geometric shape of transfer girder with an opening (adapted from Liang *et al*. 2000)



(b) Finite element model and optimized shape

Fig. 6 Evolutionary structural optimization for transfer girder with opening

3.5 Strengths of struts and nodal zones

After developing an STM by using the plane truss menu system, the compressive elements (struts) and tensile elements (ties) of the model are found by conducting the linear elastic finite element analysis of the developed STM. In the finite element analysis, the struts and ties are assumed to have unit values of axial rigidity. Next, by inputting material properties, the effective strengths of struts, ties, and nodal zones, are evaluated. As the cross-sectional areas of struts, the cross-sectional forces of ties, and the shapes of nodal zones ties are influenced by their effective strengths, they must be determined reasonably and accurately.

In general, the yield strengths of reinforcing bars are taken as the effective strengths of steel ties. However, different values and equations for concrete struts and nodal zones have been recommended by many design codes and researchers. In the present program, the effective strengths of concrete struts and nodal zones are determined either from the current design codes (EC2 2004, FIB 2010, AASHTO 2018, ACI 318 2019) or Yun's (2016, 2020) numerical methods. The tensile strains of steel ties in the perpendicular directions of each concrete strut are required in order to determine the effective strengths of concrete struts by using AASHTO LFRD (2014) design code. In a statically determinate STM, the strains are easily obtained as the strains are independent of the stiffness of struts and ties of the STM. However, in an internally (or externally) indeterminate STM, the strains cannot be obtained without conducting repetitive numerical structural analyses of the STM as the stiffness (cross-sectional areas) of struts and ties are dependent on the effective strengths of struts and ties and tensile strains of ties. In the present

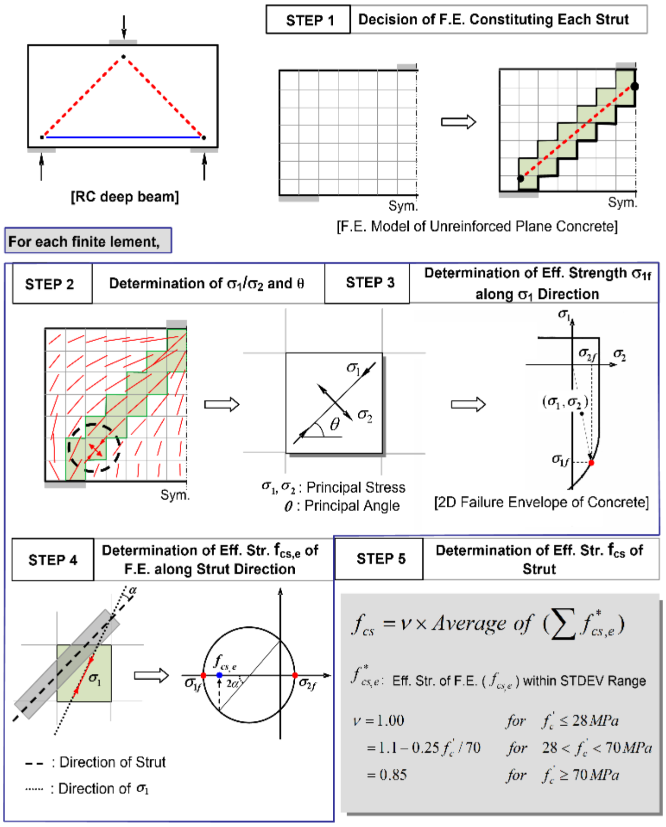


Fig. 7 Procedures for evaluating effective strengths of concrete struts

program, a program associated with two optimization techniques (a micro genetic algorithm and a simple algorithm with a trial and error procedure) is loaded to determine the effective strengths of concrete struts.

In Yun's (2016, 2020), it is shown that the numerical methods accurately determine effective strength values. Key factors (including the states of stresses at the locations of struts and nodal zones, the deviation angles between concrete struts and principal compressive stress trajectories, the degree of concrete confinements by reinforcing bars) influencing the effective strengths of concrete struts and nodal zones are accounted for. The ideas employed in Yun's method for strut strengths are shown in Figs. 5 and 7. As the variable effective strength values of a concrete strut along the longitudinal length of the concrete strut can be determined by his methods, more realistic cross-sectional shapes, including bottle and fan shapes, can be provided. In spite of the advantages of his methods, it has not been so useful in practice due to the somewhat complicated and iterative numerical procedures of the methods. The author implemented the methods in the program of the present study. For more details on this approach see the references.

3.6 Dimensioning of STM

Dimensioning is defined in three steps: (i) determination of the required cross-sectional areas of struts and ties under design loads, (ii) verification of the geometrical compatibility conditions of

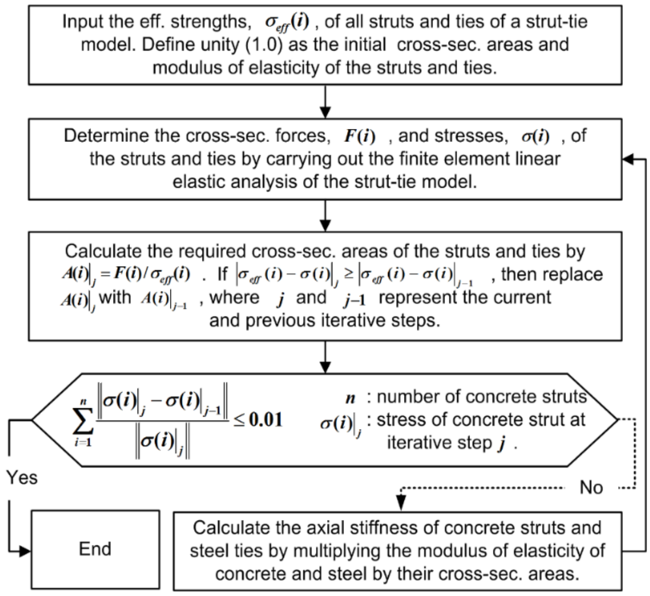


Fig. 8 Algorithm for determining cross-sectional areas (forces) of struts and ties

developed STM, and (iii) determination of reinforcement details. Here, checking the geometrical compatibility conditions implies to examine the strength of concrete struts and nodal zones by comparing the available cross-sectional areas of concrete struts and nodal zone boundaries with the corresponding required cross-sectional areas. The overlap of the cross-sectional areas of two concrete struts or the deviation of the cross-sectional area of a concrete strut from the boundary of structural concrete violates the geometrical compatibility condition, too.

In the program presented in this paper, the required cross-sectional areas and forces of struts and ties are determined by using the menu for STM analysis. In the menu, two optimization techniques, a micro genetic algorithm (Gen *et al*. 2008) and a simple algorithm (shown in Fig. 8) requiring a trial and error procedure to satisfy the conditional Eq. (5), are associated. In particular, the algorithm is useful and necessary for the cases of statically indeterminate STMs.

$$\begin{aligned} P_{rs} &\leq \varphi_s A_{strut}\ f_s \\ P_{rt} &\leq \varphi_t A_{tie}\ f_t \end{aligned} \tag{5}$$

where, P_{rs} and P_{rt} are the required strengths of strut and tie, and φ_s and φ_t are the coefficients of effective strengths f_s and f_t of strut and tie, respectively. By the menu for STM analysis, the nonlinear structural behavior and ultimate strength of concrete members can also be evaluated by employ- ing the nonlinear STM method (Yun 2000).

After determining the cross-sectional areas of concrete struts and nodal zones, the appropriateness of developed STM needs to be examined. This is accomplished by verifying the strengths of concrete struts and nodal zones. As mentioned above, the strengths are verified by comparing the required cross-sectional areas with the available cross-sectional areas. Determination of the available areas of struts and nodal zones requires considerable time and effort. Further, shaping and dimensioning nodal zones by using graphical procedures with a designer's subjectivity is also quite laborious. Above all, this approach works consistently only in

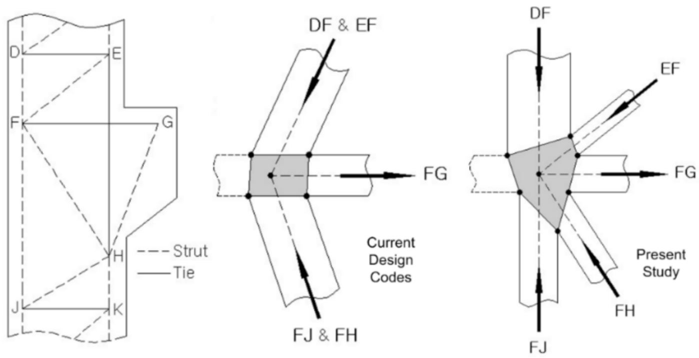
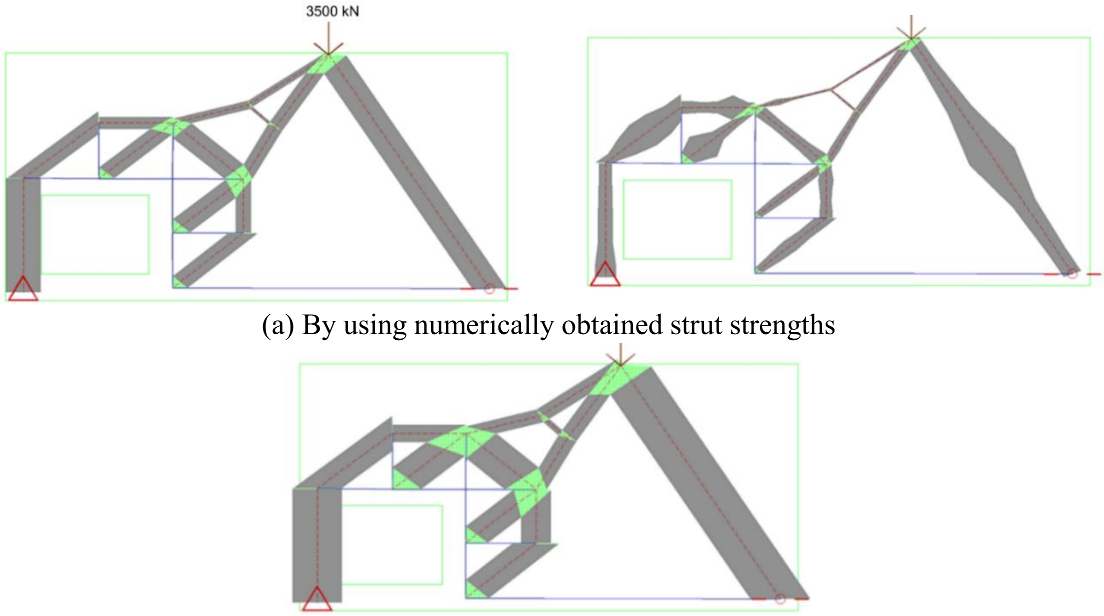


Fig. 9 Construction of nodal zone shape



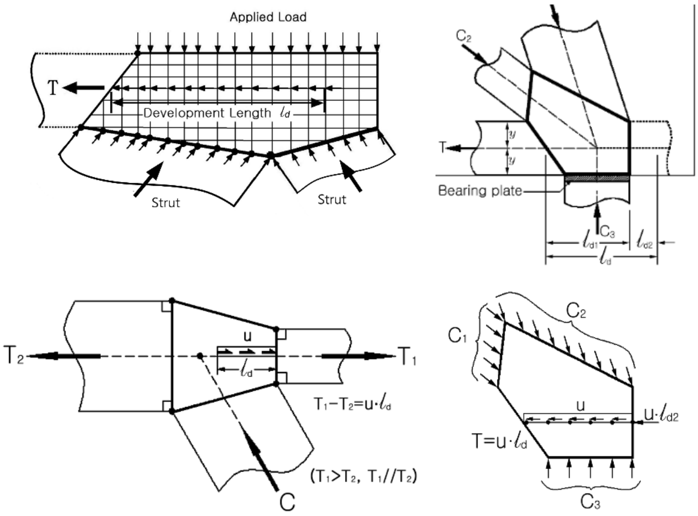
(a) By using numerically obtained strut strengths

(b) By using ACI 318 strut strengths

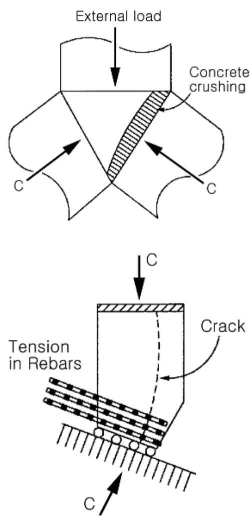
Fig. 10 Dimensioned STM for deep beam with opening

nodal zones formed by bearing plate(s), accordingly for the concrete struts framing the nodal zone. For the other nodal zones shaped without bearing plate, because of conceptual ambiguity in determining the available areas, different shapes of nodal zones and available areas of struts may be obtained according to designers' decisions (ACI 445 2010, KCI 2012). In the present program, this problem is eliminated by adopting the approach that verifies the strength conditions of concrete struts and nodal zones by examining the geometrical constraint conditions visually. Here, the boundaries of a nodal zone are determined by the intersection of the stress fields framing the nodal zone. The concept adopted in the program for forming the shape of a nodal zone is illustrated in Fig. 9.

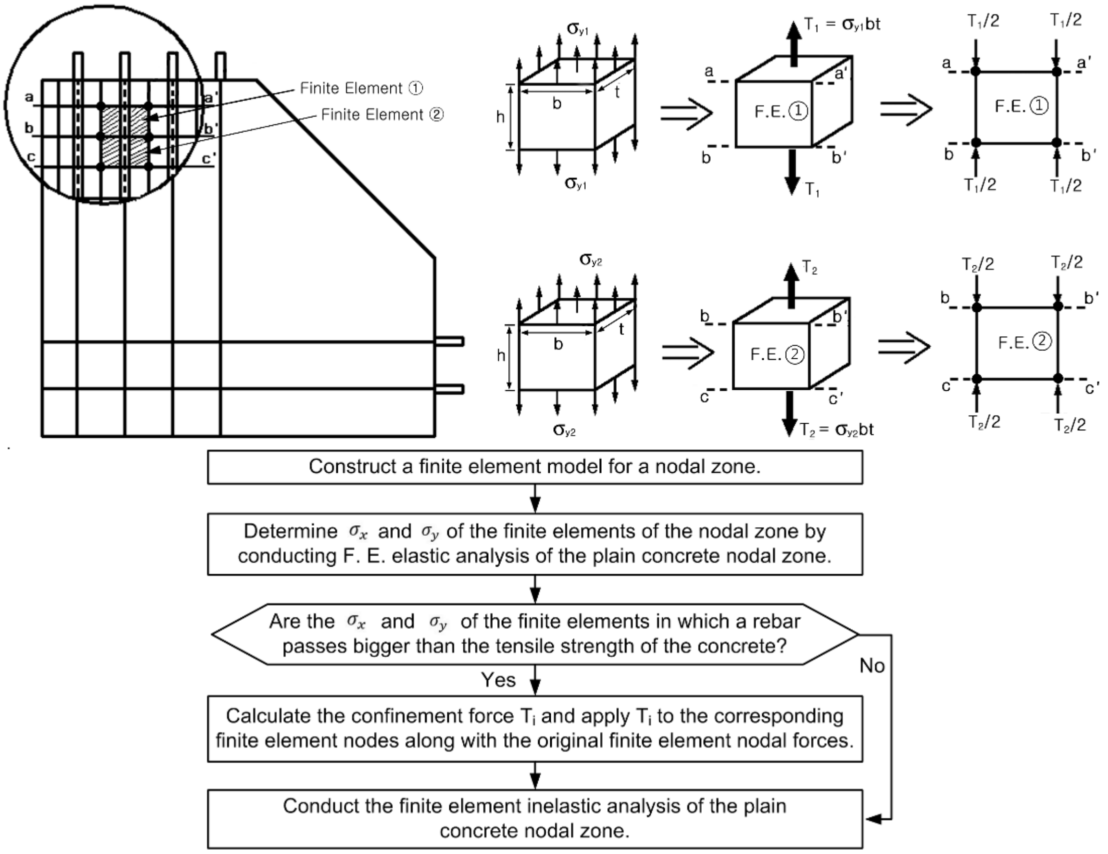
An example is shown in Fig. 10, where the geometrical constraint condition is verified by the present program for the STM of deep beam with an opening (Fig. 6(a)). In the example, the



(a) Strut and tie forces imposed to finite element nodes of nodal zones



(b) Crushing and cracking failure mechanisms



(c) Algorithm for considering confinement effect by reinforcing bars

Fig. 11 Imposition of nodal forces, failure mechanisms, and consideration of confinement effects for finite element effective strengths of concrete struts and nodal zones were determined by using the Yun's (2016) numerical method and ACI 318 (2019). For comparison, 0.75 was taken as the strength reduction factors for concrete strut and steel tie. It is shown that, under the same design circumstances, the geometrical constraint condition of the deep beam model is not satisfied with the effective strengths determined by the ACI 318 (2019).

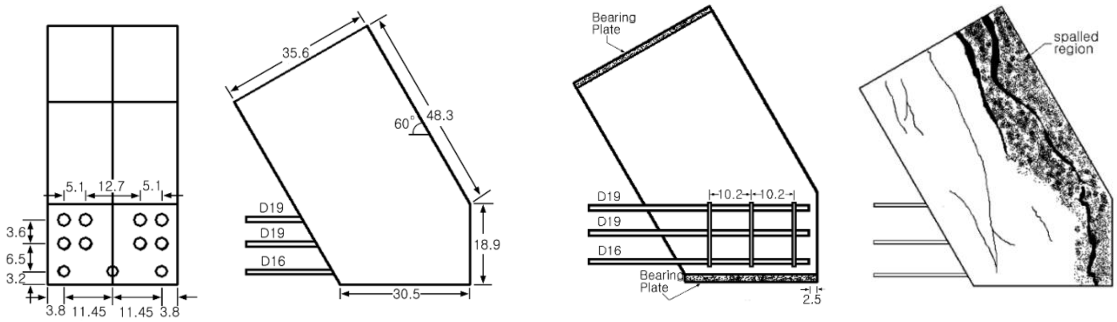
For the STM design of structural members by the ACI 445 (2010) and KCI (2012) methods, the available areas of concrete struts must be determined to verify the strength condition of concrete struts. However, the available areas cannot be identified rationally in the general STMs. Thus, a subjective decision by a structural designer, which may not be acknowledged by others, is necessary. This situation happens quite often in STM designs. This problem can be surmounted by the present program, where the dimensioned shapes of concrete struts are displayed to allow the visual verification of the strength condition of concrete struts. In the current program, a program that enables us to calculate the available areas of struts and nodal zones by a numerical approach is also loaded. The strength condition of concrete struts is examined simply by comparing the required areas and available areas of concrete struts.

3.7 Strength verification of isolated nodal zones

In the STM method of current design codes, the assumption that all the nodal zones in an STM are formed by only three elements (3 struts, 2 struts and 1 tie, 1 strut and 2 ties, 3 ties) is introduced. The nodal zones are named as CCC-, CCT-, and CTT-nodal zones according to the types and numbers of elements framing the nodal zones. Besides, to examine the strength conditions of nodal zones, the required cross-sectional areas at the boundaries of nodal zones are determined based on the above assumption. Though the approach may have an advantage in a practical point of view, there are criticisms that the approach cannot represent the characteristics of ultimate strengths and failure behaviors of nodal zones suitably in the STM analysis and design. Compared to the researches on the effective strength of concrete strut, lesser studies on nodal zones have been conducted as the failure behaviors of nodal zones are much complicated and depend on a number of factors including 1) the degree of confinement of nodal zones by reactions, compression struts, anchorage plates for prestressing, and various types of reinforcing bars, 2) the effects of strain discontinuities within the nodal zone, and 3) the splitting stresses and hook bearing stresses resulting from the anchorage of the reinforcing bars of a tension tie in or immediately behind the nodal zone.

To supplement the shortcomings of current design codes, a method utilizing a finite element inelastic analysis technique associated with a concept of failure mechanism of the nodal zone was proposed by Yun (2006). In his method, the shapes of nodal zones are formed by connecting the intersection points of boundary lines of struts and ties, as shown in Fig. 10. Besides, to reflect the effects of the factors mentioned above, the cross-sectional forces of steel struts and steel ties are applied to the finite element models of nodal zones by taking account of distribution patterns of reinforcing bars, anchorage types of reinforcing bars, and confinement of concrete by reinforcing bars. The procedure for switching the cross-sectional forces of concrete strut and steel tie to finite element nodal forces, the method for considering the effect of concrete confinement due to reinforcing bars, and the definition of cracking and crushing failure mechanisms of nodal zones are illustrated in Fig. 11.

In the present program, all the nodal zones can be treated as isolated ones, and the shape of each isolated nodal zone is formed automatically. By the plane solid menu system, a finite element



(a) Geometrical shape, re-bar details, and failure mode of specimen LFT-R

(b) Cracked and crushed shapes at 97.5% and 100 % of experimental failure load

Fig. 12 Finite element inelastic analysis of isolated nodal zone LFT-R (adapted from Yun 2006)

model of an isolated nodal zone, with the automatic imposition of finite element nodal forces, is formed. And then, the features of crack propagation, localized crushing of concrete, failure mechanism, and principal compressive stress trajectories are visualized at each incremental loading step of the linear inelastic finite element analysis of an isolated nodal zone. The predicted failure strength is the same as the accumulated load at the incremental loading step that a crushing or cracking failure mechanism occurs. An example that evaluates the failure strength of an isolated CCT nodal zone tested by Bouadi (1989) by using the present program is shown in Fig. 12. The material properties of concrete and steel of the nodal zone specimen, test setup, and test results according to the magnitude of applied load are introduced in the reference. In Fig. 12(b), three of the finite elements under the steel plate have been crushed at the last incremental loading step, which is different from the test result. The crushing phenomenon, however, is not a failure mode of the nodal zone since the other uncrushed elements can carry the additional load. The analysis results indicate that the finite element material nonlinear analysis of the nodal zone predicts a compression failure mode of the nodal zone closely, as well as 100% of the ultimate strength of the nodal zone.

4. Conclusions

STMs have proven to be useful for the design and detailing of D-regions of structural concrete. This method promotes a better understanding of force transfer mechanisms and improves the designers' ability to handle unusual circumstances. However, the method requires iterative numerical structural analyses, numerous graphical calculations, considerable time and effort, and designer's judgement in many steps of the design process. To overcome these obstacles, a few computer-based analysis and design tools have been developed. However, these programs have some limitations handling the uncertainties of the STM method in evaluating axial rigidity of struts and ties, determining and verifying the strength of struts and nodal zones, and describing the cross-sectional shapes of struts. The user-oriented graphics functions for the pre- and post-processors of numerical analysis are not sufficient, too.

In this paper, a graphics program that overcomes the limitations and disadvantages of previous programs described above is presented. The main improvements are:

- The graphical user interface for displaying the outcomes of modeling, analysis, and design of structural concrete is provided. High efficiency and convenience in the application of the STM method are obtainable by the various graphics functions of the program.
- The programs for efficient and accurate STM analysis and design, including the finite element programs for linear elastic or inelastic analyses of plane solid and truss structures subjected to all types of possible boundary conditions are incorporated.
- A program for reflecting the effects of reinforcing bars on the finite element models of plane solid and truss structures is provided.
- The programs for determining the effective strengths of struts and nodal zones accurately by eliminating the uncertainties of provisions of current design codes are loaded.

A program for displaying various shapes of cross-sections of concrete struts and nodal zones for precisestrength verifications of struts and nodal zones is provided.

The program presented in this paper has numerous numerical and convenient user-oriented graphics functions for practical applications of the STM method. The experienced structural designer with knowledge about the finite element and STM methods will benefit great deal from this program in design of structural concrete.

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References

ACI-ASCE Committee 445 (2010), *Further Examples for the Design of Structural Concrete with Strut-and-Tie Models; SP-273*, American Concrete Institute, Farmington Hills, Michigan, U.S.A.

Alshegeir, A. and Ramirez, J.A. (1992), "Computer graphics in detailing strut-tie models", *J. Comput. Civil Eng., ASCE*, **6**(2), 220-232. https://doi.org/10.1061/(ASCE)0887-3801(1992)6:2(220).

American Association of State Highway and Transportation Officials (2014), *AASHTO LRFD Bridge Design Specifications*, Washington D.C., U.S.A.

American Association of State Highway and Transportation Officials (2018), *AASHTO LRFD Bridge Design Specifications*, Washington D.C., U.S.A.

American Concrete Institute (2019), *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (318R-19)*, Farmington Hills, U.S.A.

Bouadi, A. (1989), "Behavior of CCT Nodes in Structural Concrete Strut-and-Tie Models", Master Thesis, University of Texas at Austin, Austin, U.S.A.

Chetchotisak, P., Yindeesuk, S. and Teerawong, J. (2017), "Interactive strut-and-tie-model for shear strength prediction of RC pile caps", *Comput. Concrete*, **20**(3), 329-338. http://doi.org/10.12989/cac.2017.20.3.329.

European Committee for Standardization (2004), *Eurocode 2: Design of Concrete Structures*, Brussels, Belgium.

FIB (International Federation for Structural Concrete) (2010), *CEP-FIP Model Code 2010*, Comité Euro-International du Béton, Lausanne, Switzerland.

Gen, M., Cheng, R., and Lin, L. (2008), *Network Models and Optimization*, Springer, Switzerland.

Hassoun, M.N. and Al-Manaseer, A. (2020), *Structural Concrete: Theory and Design*, John Wiley & Sons, Inc., U.S.A.

Jhong, J.T., Wang, L., Deng, P. and Zhou Man (2017), "A new evaluation procedure for the strut-and-tie models of the disturbed regions of reinforced concrete structures", *Eng. Struct.*, **148**, 660-672. https://doi.org/10.1016/j.engstruct.2017.07.012

KCI Shear-Torsion Committee (2012), *Examples for Strut-Tie Model Design of Structural Concrete*, Kimoon-Dang, Seoul, Korea.

Liang, Q.Q., Uy, B. and Steven, G.P. (2002), "Performance-based optimization for strut-and-tie modeling of structural Concrete", *J. Struct. Engineering, ASCE*, **128**(6), 815-823. https://doi.org/10.1061/(ASCE)0733-9445(2002)128:6(815).

Liang, Q.Q., Xie, Y.M. and Steven, G.P. (2000), "Topology optimization of strut-and-tie models in reinforced concrete structures using an evolutionary", *ACI Struct. J.*, **97**(2), 322-330. http://www.concrete.org/PUBS/JOURNALS/SJHOME.ASP.

MacGregor, J.G. (2019), *Reinforced Concrete - Mechanics and Design*, Prentice Hall, Inc., Upper Saddle River, U.S.A.

Mish, K., Nobari, F. and Liu, D. (1995), "An interactive graphical strut-and-tie application", *Proceedings of the Second Congress on Computing in Civil Engineering*, American Society of Civil Engineers, New York, 788-795.

Özkal, F.M. and Uysal, H. (2017), "Reinforcement detailing of a corbel via an integrated strut-and-tie modeling approach", *Comput. Concrete*, **19**(5), 589-597. https://doi.org/10.12989/cac.2017.19.5.589.

Parol, J., Al-Qazweeni, J. and Salam, S.A. (2018), "Analysis of reinforced concrete corbel beams using Strut and Tie models", *Comput. Concrete*, **21**(1), 95-102. https://doi.org/10.12989/cac.2018.21.1.095.

Schlaich, J., Schaefer, K. and Jennewein, M. (1987), "Towards a consistent design of structural concrete", *J. Prestressed Concrete Institute*, **32**(3), 74-150. https://doi.org/10.15554/pcij.05011987.74.150.

Tech Soft 3D (1997), "HOOPS 3D Graphics System", Bend, Oregon.

Tjhin, T.N. and Kuchma, D.A. (2002), "Computer-based tools for design by strut-and-tie method: advances and challenges", *ACI Struct. J.*, **99**(5), 586-594.

Tran, C.T.C., Nguyen, X.H., Nguyen, H.C. and Vu, N.S. (2020), "Strut-and-tie model for shear capacity of corroded reinforced concrete columns", *Advan. Concrete Construct.*, **10**(3), 185-193. https://doi.org/10.12989/acc.2020.10.3.185.

Xia, Y., Langelaar, M. and Nendriks, M.A.N. (2020), "A critical evaluation of topology optimization results for strut-and-tie modeling of reinforced concrete", *Comput. Aided Civil Infrastruct. Eng.*, **35**(8), 850-869. https://doi.org/10.1111/mice.12537.

Yun, Y.M. (2000), "Computer graphics for nonlinear strut-tie model approach", *J. Comput. Civil Eng., ASCE*, **14**(2), 127-133. https://doi.org/10.1061/(ASCE)0887-3801(2000)14:2(127).

Yun, Y.M. (2000), "Nonlinear strut-tie model approach for structural concrete", *ACI Struct. J.*, **97**(4), 581-590.

Yun, Y.M. (2006), "Strength of two-dimensional nodal zones in strut-tie models", *J. Struct. Eng., ASCE*, **132**(11), 1764-1783. https://doi.org/10.1061/(ASCE)0733-9445(2006)132:11(1764).

Yun, Y.M. (2020), "Numerical method for effective strength of nodal zones in two-dimensional strut-and-tie models", *J. Korea Concrete Institute*, **32**(4), 359-369. https://doi.org/10.4334 /JKCI.2020.32.4.359.

Yun, Y.M. and Ramirez, J.A. (2016), "Strength of concrete struts in three-dimensional strut-tie models", *J. Struct. Eng., ASCE*, **142**(11). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001584.

Yun, Y.M., Kim, B.H. and Ramirez, J.A. (2018), "Three-dimensional grid strut-and-tie model approach in structural concrete design", *ACI Struct. J.*, **115**(1), 15-26. https://doi.org/10.14359/51700791.

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