



## **Strut-and-Tie Modelling and Design for High Strength Concrete**

by Ir. Dr Ng Soon Ching

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The one day pre-conference course on strut-and-tie modelling, and design with high strength concrete was organised by the Civil & Structural Engineering Technical Division (CSETD) on 11 August 2014. The speaker, Prof Stephen Foster, is the head of School of Civil and Environmental Engineering at University of New South Wales (UNSW), Australia.

Prof Foster has more than 30 years of experience in research and has published over 240 research journals. Much of his last 13 years has been focused on steel fibre reinforced concrete (SFRC) and ultra-high performance concrete (UHPC).

This pre-conference course was chaired by Adjunct Prof Ir. MC Hee and attended by 55 participants.

The pre-conference course was divided into five sessions: modelling non-flexural members; reinforced concrete members using linear stress analysis; reinforced concrete members using non-linear analysis; Prof Foster's past research; and detailing of structural elements and joint connections.

### ***Modelling non-flexural members***

The definition of non-flexural members is controlled by two parameters: span-effective depth ratio; and types of member. These values may differ with different design code.

Under ACI 318, the limit value of span-effective depth ratio of continuous member is 2.5. In AS3600, the corresponding value for defining none flexural action is 4. Prof Foster pointed out that the design of structural member such as deep beam, based on strut and tie modelling method, utilised the lower bound method of plasticity that allowed the designers to specify the load path. If the designed load path requires large redistribution of forces then the strut and tie method may be non-conservative.

Under strut and tie modelling, some assumptions are made:

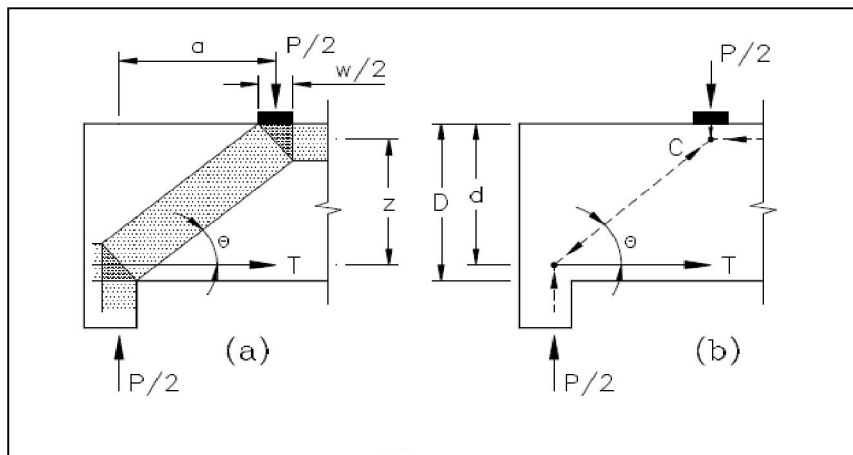
- a. Concrete and steel behave as perfectly plastic
- b. All tension resisted by all ties
- c. Struts and ties are joined at the nodes
- d. Nodes are in equilibrium
- e. Anchorage and bearing failures are avoided through good detailing

**Table 1 : Non-flexural members**

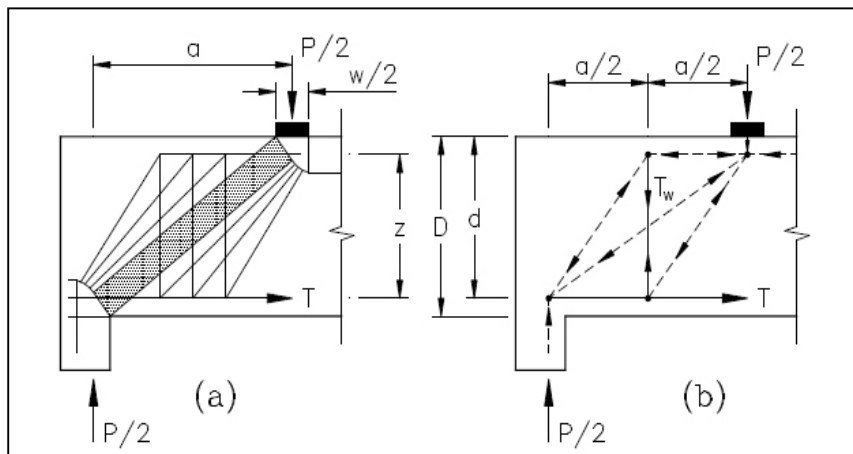
Type of members	Span/Depth ratio	
	ACI-318	AS3600
Corbels and Nibs	1	1.5
Simply Supported Members	1.25	3
Continuous Members	2.5	4

} Limit of non-flexural action
} Limit of flexural action

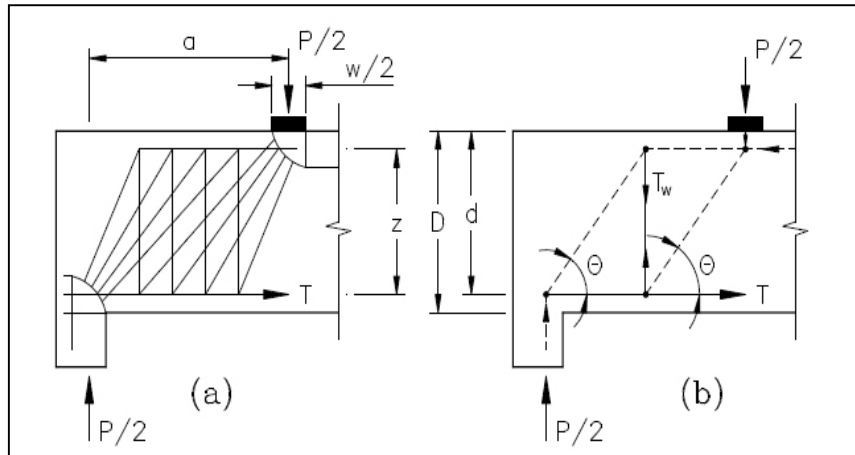
Types of strut and tie model are shown in Figure 1, 2 and 3.



**Figure 1:** Type 1 - the shear is carried from the load points to the supports directly by major struts



**Figure 2:** Type 2 - the shear is taken to the supports by a combination of primary (major) and secondary (minor) struts. Hanger reinforcement is required to return the vertical components of forces developed in the secondary struts to the top of the member



**Figure 3:** Type 3 - the shear to the supports via a series of minor struts with hanger reinforcement used to return the vertical components of the strut forces to the top of the member.

### ***Reinforced concrete members using linear stress analysis***

In Session 2, Prof Foster discussed the design of reinforced concrete membrane and shell using linear stress analysis.

He highlighted both the advantages and disadvantages of using linear stress analysis. The advantages include ease to apply, multiple load cases are accommodated quickly and the greatest quantity of reinforcement placed in the high tension regions can assist in controlling crack propagation. As for the disadvantages, there is no information to be attained on the collapse load of the structure, information on inelastic phenomenon such as crack width, crack spacing and deflection is not provided.

In addition, the detailing guidelines need to be established in order to ensure ductility and serviceability limit to be met.

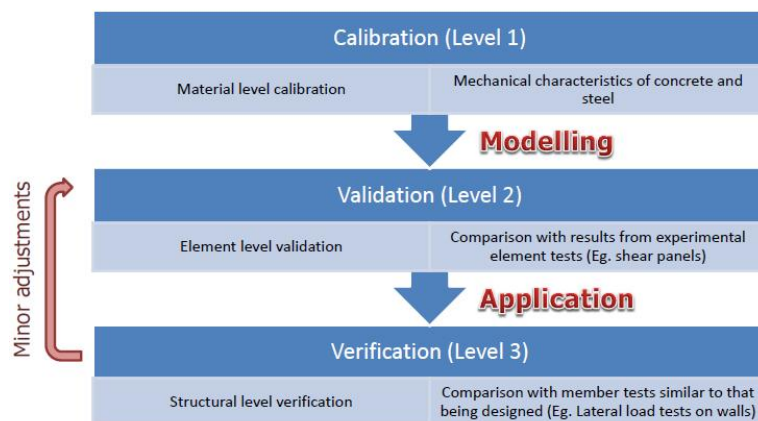
Prof Foster showed a few examples of finite element (FE) outputs and calculations based on linear analysis. "The limit design based on linear stress analysis is a powerful tool for dimensioning reinforced concrete membrane structures with its foundation in the lower bound of plasticity", he added.

### ***Reinforced concrete members using non-linear analysis***

In this session Prof Foster continued his topic on design of reinforced concrete members but based on non-linear stress analysis.

This method is a useful tool for forensic analysis and assessment of existing structures. However, Prof Foster cautioned that this method must be used with great care. As a matter of fact, FE modelling is not matured to the point where the designer can simply develop a geometrical model of the structure. Hence, it is mandatory for the designer to evaluate the programs capability before

assessing a structure or structural element. For the non-linear stress analysis, designer needs to do calibration in the program such as material properties of concrete and steel, validate the program output by comparing results with experimental element tests, and finally, verified it with the similar structural members being designed.



**Figure 4 :** Model calibration and verification for non-linear analysis

### ***Outcomes of past research***

Prof Foster presented his past research works related to ultra-high performance concrete (UHPC) and steel fibre reinforced concrete (SFRC).

UHPC is basically the combination of cement paste with the grade of 120 and steel fiber with the steel grade exceeding 2300 MPa. In his past research, Prof Foster together with his former PhD students had conducted extensive tests on UHPC with respect to flexural behaviour and shear behaviour.

On the other hand, the Australian Draft Bridge Code (DR AS5100.5) clauses have currently included measurement of post-cracking tensile strength of SFRC, design of SFRC beams for bending and shear, serviceability of SFRC members and quality control for production of SFRC.

Besides the Australian code, they are other codes such as NZS 3101-2000, ACI 318, DIN 1045: Part 1-3 and DIN EN 206-1 are starting to develop for inclusion of steel fibres in structures.

### ***Detailing of structural elements and joint connections***

In the final session, Prof Foster emphasized the importance of detailing in structural elements and joint connections.

Since the detailing involves the translation of a good structural design from the computer or calculation pad into the final structures, good detailing is crucial for ensuring that reinforcement and concrete can interact efficiently in order to provide satisfactory behaviour throughout the complete range of loading. A few examples of structural failure were explained due to poor detailing.