Journal of the Korea Academia-Industrial cooperation Society
Vol. 15, No. 10 pp. 6329-6335, 2014

http://dx.doi.org/10.5762/KAIS.2014.15.10.6329
ISSN 1975-4701 / eISSN 2288-4688

Design Comparison by Node Width Variation of Strut-Tie-Model

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스트럿-타이 모델의 절점 폭 변화에 따른 설계 비교

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Abstract In the Strut-Tie-Model(STM), the width of a node is important in both analysis and design. Its effects on the force distribution at truss analogy system. In addition, it effects the verification of all struts and nodes, which need to be checked to satisfy the code of design. Code here refers to the ACI-318 code. Four methods were used to define the width of node: 1) effective depth is assumed to equal to 0.9 of the overall depth of beam, 2) moment equilibrium 3) assumption of the width of node at the bottom equal to 380mm, and 4) the new proposed method by this study. 106 selected samples of a parametric study obtained from the four methods were analyzed. Because total steel requirement from these four methods are similar, the easiest would be a good choice for a time saving calculation.

요 약 스트럿-타이 모델에서 절점 폭은 해석과 설계에서 중요하다. 그것은 트러스 유사 시스템에서 힘의 분포에 영향을 준다. 또한, 설계 코드를 만족시키기 위한 모든 스트럿 및 절점의 검증에도 영향을 미친다. 여기서 코드는 ACI-318 코드를 의미한다. 절점 폭을 결정하는 4가지 방법이 있다. 즉 1)유효 깊이를 보 높이의 0.9배로 가정하는 방법 2)모멘트 평형을 이용하는 방법 3)절점 폭을 380mm로 가정하는 방법 그리고 4)본 연구에서 제안된 방법이다. 106개의 파라미터 연구를 분석하였다. 그 결과 필요로 하는 총 강재량이 4가지 방법 모두 크게 차이가 나지 않기 때문에 가장 쉬운 방법으로 선택하는 것이 시간 절약 측면에서 좋을 것으로 판단된다.

Key Words : ACI, deep beam, node width, STM

1. Introduction

In strut-and-tie model(STM), width of nodes are very important for design. It effects on lever arm which determines angle(θ) between strut and tie that gives amount of force which is taken from truss analogy and it strongly effects on strut and node verification. The smaller of width of node the better for force distribution [3], but it might be not good for stress bearing capacity check in term of verification to satisfy the code, ACI 318-11[1]. There are several different methods to be used for deep beam designed by STM recently. Some designers simply use the simplest one whist other try to use the complex but most accuracy one and the other try proposing their new method for their design. Each methods have their pros and cons; However, in this paper we selected four kind of methods, including one new proposed, which comes up from our experiences of deep design, of determining width of node specifically for deep beam which is designed by STM. By having these four methods compared, we will find the most appropriate method

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Received February 24, 2014 Revised (1st September 2, 2014, 2nd September 17, 2014) Accepted October 10, 2014

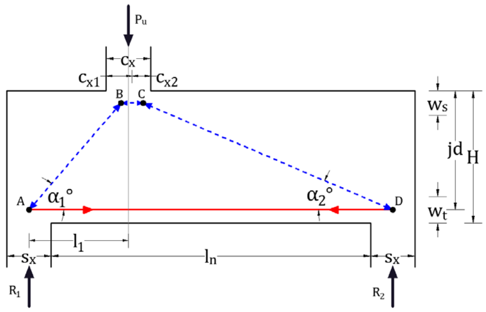
which suite to the condition of the design. The first and simplest one is to assume effective of depth of a beam equal to 0.9 of overall depth beam [4]. The second one is using moment equilibrium and solve for second degree equation which is functioned to each of width of node [3]. The third one is an assumption of width of node at bottom and solve for the first trial to get the angle between strut and tie [2]. The last one which is newly proposed is an assumption of the relation between clear span and overall depth of beam in ratio of clear span-to-overall depth is equal to 3. The purpose of this study is to find the effect of each method of width of node determination applied in deep beam for STM design method and short out the appropriate method including the newly propose for efficiency use and to have a new comparison which related to clear span and overall depth ratio. More over, if the results show that these four methods give not much different of total steel provision, the most simplest one should be acceptable chosen in term of time saving of calculation procedure [7].

2. Research Significant and Objective

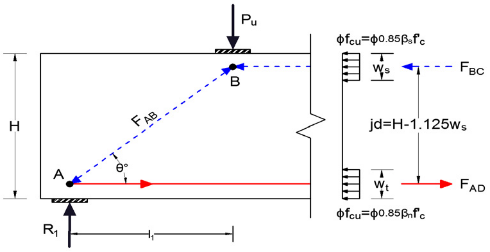
The presented research contributes to amount of different of method of width of node through the comparison between two type of STM(s). More than this, it gives structural engineering more idea of choosing which design method is should be used and in which situation. By choosing the most appropriate one, we can save time and have it being used affectively.

3. Four methods of node width assumption

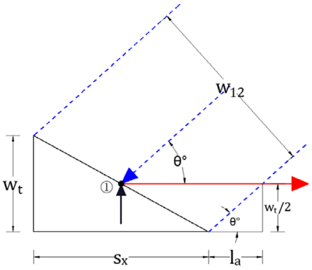
First we need to find the relationship between width of strut and width of node. By using free body diagram in Fig.1~Fig.3, width of nodes are found functioning to each other.



[Fig. 1] Strut-and-tie model (STM)



[Fig. 2] Free body diagram



[Fig. 3] Width of node in detail

$$F_{BC} = \phi F_{nc} = \phi f_{cu} A_c = \phi(0.85\beta_s f'_c) b w_s \quad \text{(eq.1)}$$

where $\beta_s = 1$ (prismatic)

$$F_{AD} = \phi F_{nt} = \phi f_{cu} A_c = \phi(0.85\beta_n f'_c) b w_s \quad \text{(eq.2)}$$

where $\beta_n = 0.8$ (CCT : Compression-Compression-Tension)

(eq.1) & (eq.2) we get;

$$w_t = 1.25 w_s \text{ or } w_s = 0.8 w_t \quad \text{(eq. 3a, 3b)}$$

3.1 Method 1(w_{st1})

It is assumed that effective depth of the beam is equal to 0.9 of overall depth of the beam [4]. Finally width of strut and width of node functions to only depth of beam.

$$jd = H - \frac{w_t}{2} - \frac{w_s}{2} \quad \text{(eq. 4)}$$

where; jd is lever arm, $j = 0.9, d = 0.9H$

(eq.3) & (eq.4) we get $jd = H - 1.125w_s$ (eq.5)

$w_t = 0.211H$, $w_s = 0.169H$

3.2 Method 2(w_{st2})

By moment equilibrium about point A (see Fig. 2) we get;

$$p_u l_1 - F_{BC} jd = 0 \quad \text{(eq.6)}$$

substitute (eq.1) in (eq.6) we get second degree equation with function to w_s. Solve for w_s.

3.3 Method 3(w_{st3})

In this case first width of node at bottom is assumed to equal to 380mm [4] to get lever arm (jd) then check for verification. By using jd angle θ between tie AD and strut AB (see Fig. 1) is defined. F_{AD} and F_{AB} are defined by truss method. Check capacity at point A then define the new of width of strut and width of node by (eq.8) as bellow.

$$w_t = \frac{F_{AD}}{f'_c d} \quad \text{(eq.8)}$$

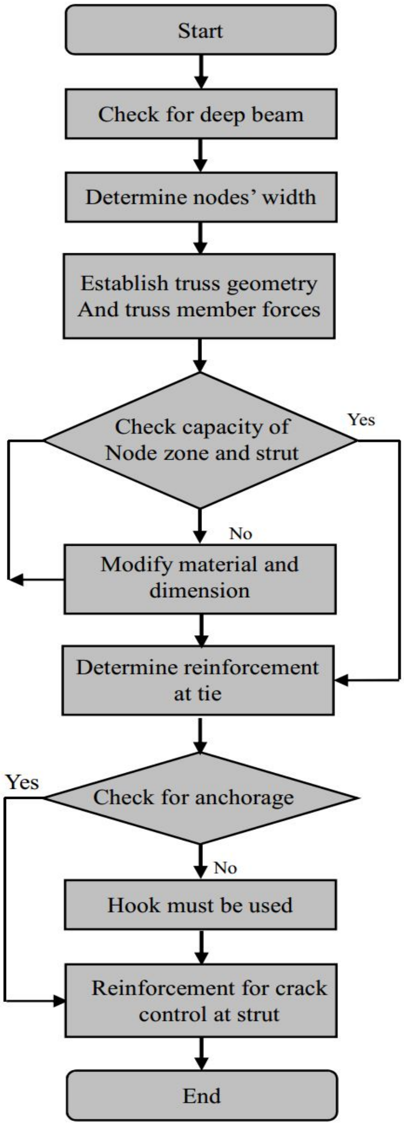
where f'_c is compressive strength of concrete

3.4 Method 4(w_{st4})

Based on the above methods, this proposed method [4,5] is assumed that the condition of clear span-to-depth ratio is less than or equal to 3 then $w_t = 0.2H$ but if it is more than 3 $w_t = 0.3H$. $w_s = 0.8w_t$ as all above.

4. Strut-and-tie model

First, establish the STM and determine the required truss forces as shown in [Fig. 1]. Second, check bearing capacity at every node and strut. Finally, determine reinforcement. For tie element, main rebar are provided, whereas, strength of struts are used for shear reinforcement. Checking the anchorage should be done and in case available length of anchorage is smaller than require anchorage, hook must be use. But in reality, hook shall be used for main rebar, so although available of anchorage is bigger than require anchorage hook should be used [Fig. 4].



[Fig. 4] Deep beam design flow chart

5. Parameter Study

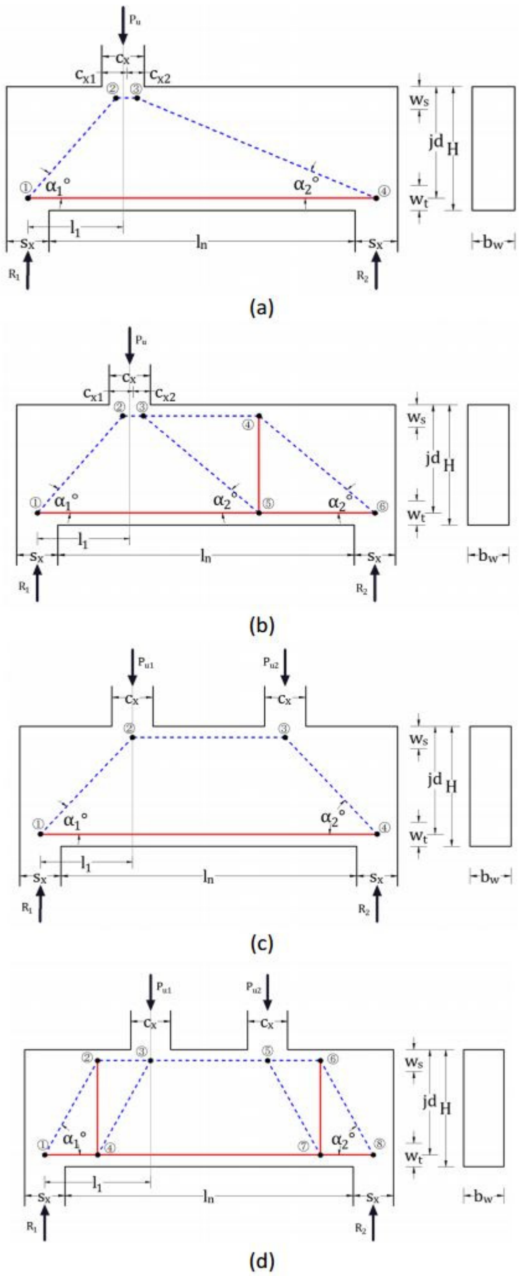
In this study, there are two main types of beam resisted by single load (p_{u1}) and symmetric two loads. There are three kinds of parameters including load location, depth of beam and loading which designed by two types of STM; simple strut-and-tie model (STM Ⅰ) and Complex strut-and-tie model (STMⅡ) (see Fig. 5). There are 106 samples of deep beam are selected to be designed and compared.

In single load study, the values of parameters are; l_1 =1.1m~2.1m, depth of beam H=1.1m~1.9m, load $p_{u1}=1000\,kN \sim 2600kN$ and for rest of other values are the same. While in two symmetric loads, the values of parameters are; $l_1=1.1m \sim 1.5m$, depth of beam H=1.1m~1.9m, load $p_{u1}=p_{u2}=500\,kN \sim 1500kN$ and for rest of other values are the same, see [Table 1]. Fig.6~11 show slightly different amount of total steel needed for various types of parameters and types of STM. More over, it should be noticed that this study is conducted by computer programming of Excel VBA for aided design so the results should be acceptable. However, since the results are taken from the final design, used for real construction, we must accept that some variations make small difference. For instant, slight difference in shear reinforcements may have the same amount of steel after reinforcement arrangement.

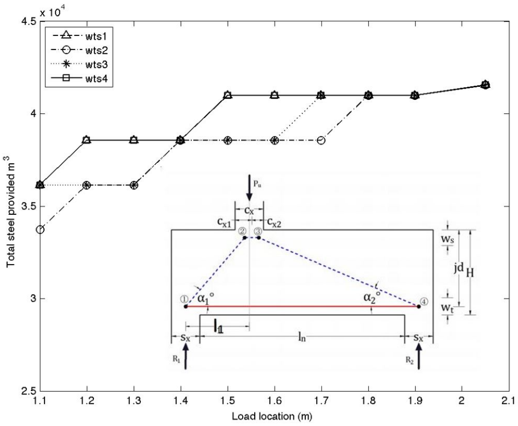
[Table 1] Geometrical properties, material properties

Para.	l_1	H	p_u	l_n	s_x	c_x	b_w	f'_c	f_y
For single load (p_{u1})									
l_1	1.1~2.1	1.5	2500	3.6	0.5	0.5	0.5	28	410
H	1.37	1.1~1.9	-	-	-	-	-	-	-
p_{u1}	-	1.5	1000-2600	-	-	-	-	-	-
For two loads $(p_{u1}=p_{u2})$									
l_1	1.1~1.5	1.2	1250	-	-	-	-	-	-
H	1.37	1.1~1.9	-	-	-	-	-	-	-
p_u	-	1.2	500-1500	-	-	-	-	-	-

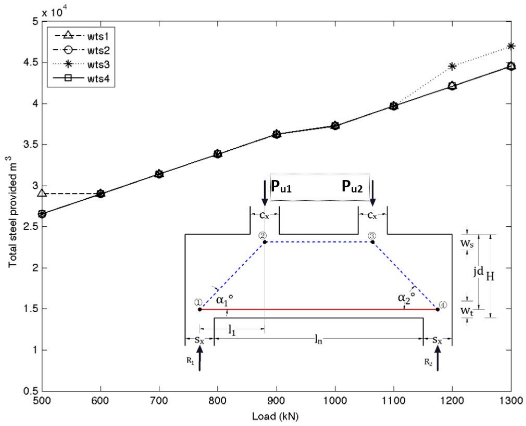
l_n,s_x,c_x,b_w,H,l_1(m), f'_c&f_y (MPa) & p_u(kN)



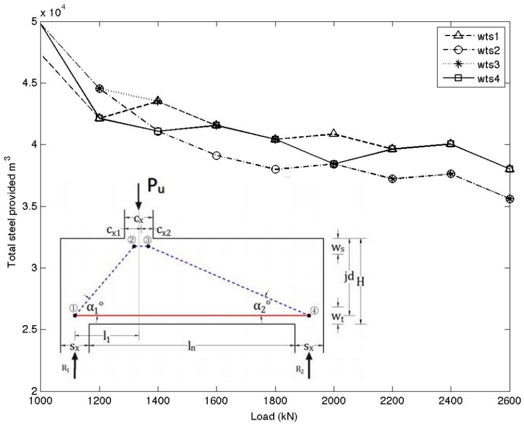
[Fig. 5] Type of Strut-and-Tie Models
(a) STM Ⅰ loaded by one concentrated load p_u
(b) STMⅡ loaded by one concentrated load p_u
(c) STM Ⅰ loaded by two loads p_{u1} and p_{u2}
(d) STMⅡ loaded by two loads p_{u1} and p_{u2}



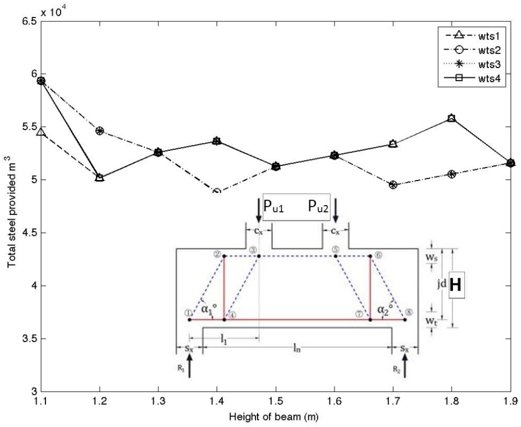
[Fig. 6] Total volume of steel provided (STM I, parameter l_1)



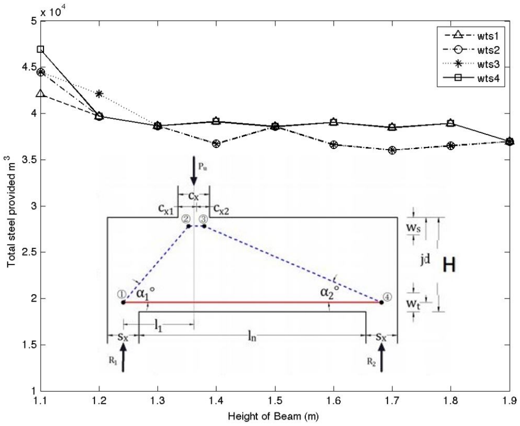
[Fig. 9] Total volume of steel provided (STMI, parameter p_u)



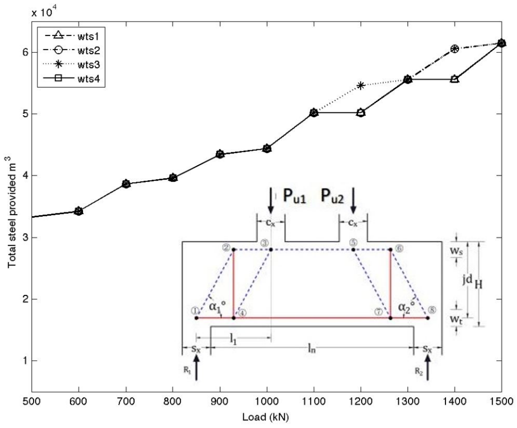
[Fig. 7] Total volume of steel provided (STM I, parameter p_u)



[Fig. 10] Total volume of steel provided (STM II, parameter H)



[Fig. 8] Total volume of steel provided (STM I, parameter H)



[Fig. 11] Total volume of steel provided (STM II, parameter p_u)

[Table 2] Total steel requirement of each w_{ts} over total of w_{ts}, $\left(w_{tsx} / \sum_{x=1}^{4} w_{tsx}\right)$

Para.		w_{ts1}	w_{ts2}	w_{ts3}	w_{ts4}
STM I	For single load (p_{u1})				
	l_1	25.39%	24.45%	24.77%	25.39%
	H	25.16%	24.60%	24.77%	25.47%
	p_{u1}	25.38%	24.47%	24.97%	25.18%
	Avg.	25.31%	24.51%	24.83%	25.35%
	For two loads ($p_{u1} = p_{u2}$)				
	l_1	24.87%	24.87%	25.39%	24.87%
	H	25.38%	24.47%	24.97%	24.78%
	p_{u1}	24.98%	25.20%	25.25%	24.78%
	Avg.	25.07%	24.78%	25.20%	24.94%
STMII	For single load (p_{u1})				
	l_1	25.39%	24.47%	24.75%	25.39%
	H	26.54%	26.00%	26.15%	26.82%
	p_{u1}	32.42%	32.01%	32.34%	32.70%
	Avg.	28.12%	27.49%	27.74%	28.30%
	For two loads ($p_{u1} = p_{u2}$)				
	l_1	24.91%	24.91%	25.27%	24.91%
	H	32.42%	32.31%	32.34%	32.70%
	p_{u1}	30.07%	30.31%	30.55%	30.07%
	Avg.	29.14%	29.07%	29.38%	29.23%

6. Results and discussion

Base on result from three different parameters of load location, depth of beam and load, w_{ts1} requires more total steel than w_{ts3}, w_{ts4} and w_{ts2} consecutively. This because w_{ts1} functions to only the depth of beam, so only changes in depth of beam takes effect while w_{ts3} bases only on assumption. w_{ts4} functions to clear span and depth of beam which are the most important parameter in deep beam and w_{ts2} is most accurate in design comparing to other three methods since in functions to many parameters. In general, w_{ts2} seems to be the most appropriate method for design, it requires less total steel than the other,, but since the differences are less 5% all the four methods require almost the same amount of total steel.

7. Conclusion

Since total steel requirement from these four methods are not far different, the easiest one would be a good choice for time saving calculation and the proposed of w_{ts4} suitable to be accepted. However for more accurate w_{ts2} should be taken into account. With assistant from program coding, we recommend w_{ts2}, and it is what we used for many study on deep beam which is designed by STM. Lastly, since deep beams are get many effects from the clear span-to-depth ratio, the width of strut and node which are taken from this ratio is reasonable to be used. We believe that this study will be useful for further research related to deep beam design by STM.

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DOI: http://dx.doi.org/10.5762/KAIS.2014.15.4.2406

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