Effect of Shear Reinforcement as Horizontal Restraint on the Bearing Capacity of Bridge Deck Slab using Strut-and-Tie Model

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Abstract *The purpose of this paper is to carry out an analysis and provide a design method for the disturbed/discontinuous regions of concrete bridge deck slab-on-girder, with simplicity and accuracy using strut-and-tie model. Strut-and-tie model in designs of reinforced concrete structures involve the use of some basic tools that include struts, ties and nodes. The method is very powerful but indirect for analysing reinforced concrete complex structures. In this study, the combined geometry of the deck slab and T-beam constituting a corbel-like geometry providing a region of geometric discontinuity produces a non-linear strain distribution. This behaviour enables the development of a modified strut-and-tie model for the system of an existing case-study Bridge. The Strut-and-tie model was developed using different types of configurations and eventually, a much simpler and precise solution is obtained. The concrete and shear reinforcement constitute the model elements in which, an efficient ultimate capacity for the system is obtained without incorporating the contribution of transverse steel reinforcement in the deck slab.*

Keywords — *Strut-and-tie, bridge deck, Finite element, T-beam, strain distribution*

I. INTRODUCTION

Strut-and-tie modelling have been a very popular method used for several years. The method is included in AASHTO LRFD Bridge specification since 1994, ACI 2002 and Eurocode. It is a very useful concept for structural engineers, and its usage in the design of reinforced concrete members was recommended by various researchers.

The strut-and-tie model which was described in Appendix A of ACI 318-2002 [1] provides a comprehensive means of structural concrete design where sectional design methods for shear and flexure are not applicable. These cases are referred to as disturbed or discontinuity regions resulted in damage or brittle failure if not properly designed and detailed.

Development of comprehensive models became necessary considering the discovery of limitations in the empirical design methods. Important works of Schlaich et al [2], [3] and the previous application of plasticity theory on the design of members under torsion and shear by Thurlimann [4], [5] and Nelson [6], [7] provided the basis for strut-and-tie models.

The strut-and-tie are good design tools as they include the use of truss models which proved to be very valuable in reinforced concrete design as used for shear design by Ritter [8], Morsh [9], [10] and Rausch [11], [12], which is even more peculiar to discontinuity regions. The innovation of atrut-and-tie models provides a unique design method with consistency in analysing both B-regions and D-regions with similar models and in addition

The innovative practical application of steel free bridges [13], [14] using the arching action behaviour significantly improved a bridge deck slab bearing capacity in which a punching shear failure instead of the assumed flexural failure from conventional design method was obtained. This arching action was achieved by providing full horizontal restraint at the transverse deck slab supports. Apparently finding other simpler means of providing such restraint to achieve a more enhanced capacity in bridge deck slab would be beneficial. An enhanced bridge stiffness has been fund to be related to its structural change from damage [15]

This paper is therefore aimed at considering the role of shear reinforcement present in concrete beam girders extending in to the top concrete slab in providing some significant restraint that would eventually enhanced the overall capacity of the deck system using Strut-and-Tie model (STM) of an existing case study bridge. The bridge considered was S.G. Tembeyoh Kota Tinggi Johor, Malaysia and its design details was obtained from Zainal and Mohammad SDN. BHD. Civil and structural consulting engineers Johor Bahru Malaysia. Slab on the T-beam and the load case 1 of the designed bridge was used to carry out the STM analysis without the inclusion of transverse steel reinforcement within the slab.

II. STRUT-AND-TIE MODEL DEVELOPMENT

The bridge deck configuration shown in Figure 1 represent a 200 mm thick slab on wide T-beam of 800 mm flange width, 160 mm shortest flange thickness and 300 mm web thickness was used to develop the strut-and-tie model.

A general purpose finite element software Abaqus 6.14 was used to analyse the deck configuration to obtain the stress flow and compute the internal member forces for the truss system representing the load path.

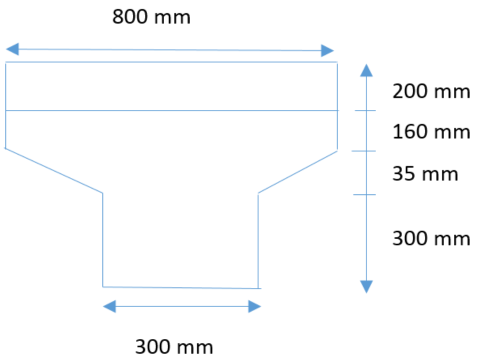

Fig 1. Slab-on-T-beam cross section

A. Delineation of D-region from Bernoulli's region

The combined T-beam flange and slab is considered to be in the disturbed-region because of its double corbel-like nature.

Central web portion might be considered as Bernoulli's-region that can be analyse using conventional method but it would be still reasonable to consider the entire area as D- region and design with

B. Boundary conditions of the truss system

To generalize the top slab and transvers T-beam flange as a truss, the struts and tie members of the truss are resisted by two supports. The concrete beam web which is much stiffer act as the support of the system configuration consisting of two reactions both of which were restrained against displacement in the vertical Y-direction and one of which additionally restrained against horizontal displacement in X-direction.

C. Load path

Finite element analysis using Abaqus software gives, the behaviour of the deck system. The finite element model generate the principle stresses in the beam flange under the action of concentrated loads at the centre and two either edges of the top slab. A 4-node bilinear plane stress quadrilateral element with elastic isotropic material property was used. The linear-elastic behaviour obtained described the critical areas of tension and compression in which the load path was revealed using the stress distribution in the member.

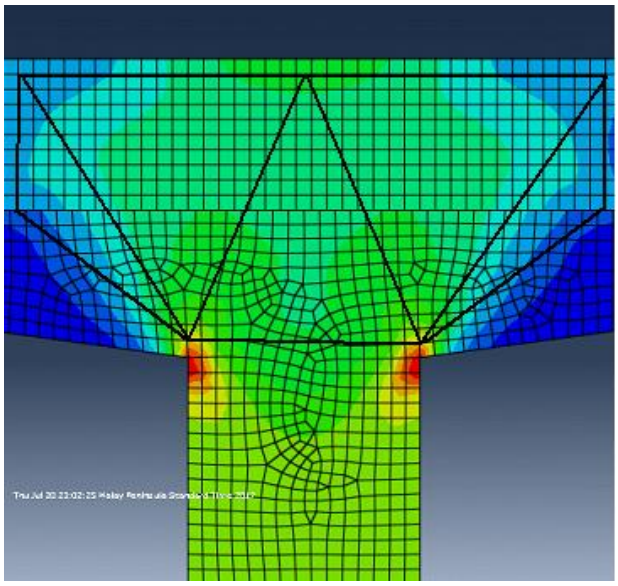

Figure 2. Stress distribution and imposed truss system representing the load path

From the stress distribution results plot, the concentration of stress distribution is portrayed as shown in figure 3. The load path is then used to determine the struts and ties orientation in the model.

D. Truss system for the model

The load path obtained from stress distribution in the previous model is then use to configure a suitable truss system for the STM. Internal forces were then obtained in which the ties and struts chosen realistically represents the stress distribution obtained from the finite element results.

The, Ties and struts geometries, elastic stress distribution, loadings and boundary conditions were used to determine the geometry of the Strut-and-tie model using trial and error to obtain a more reasonable model that perfectly resembles the flow forces.

E. Struts and ties forces

The 2D truss system now represented isthen analyse using finite element method with the same Abaqus 6.14 software.The structure is subjected to the action of three converted concentrated loads representing the case 1 bridge loadings.

Support restraint/reactions are applied at two bottom nodes located at near side ends of the T-beam web. The left side node is restrained against both horizontal and vertical displacement, while the other right node is restrained against vertical displacement. A 2-node linear element of 2-D truss elastic steel is used for all the truss members.

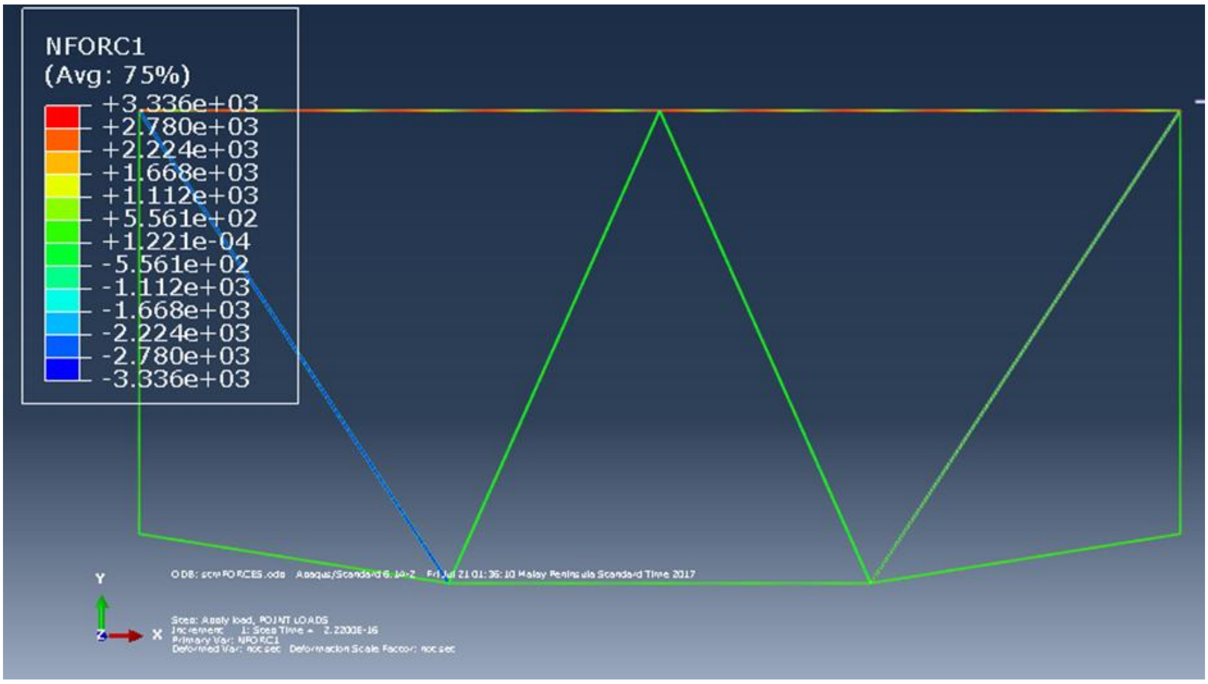

Figure 3. Member internal forces

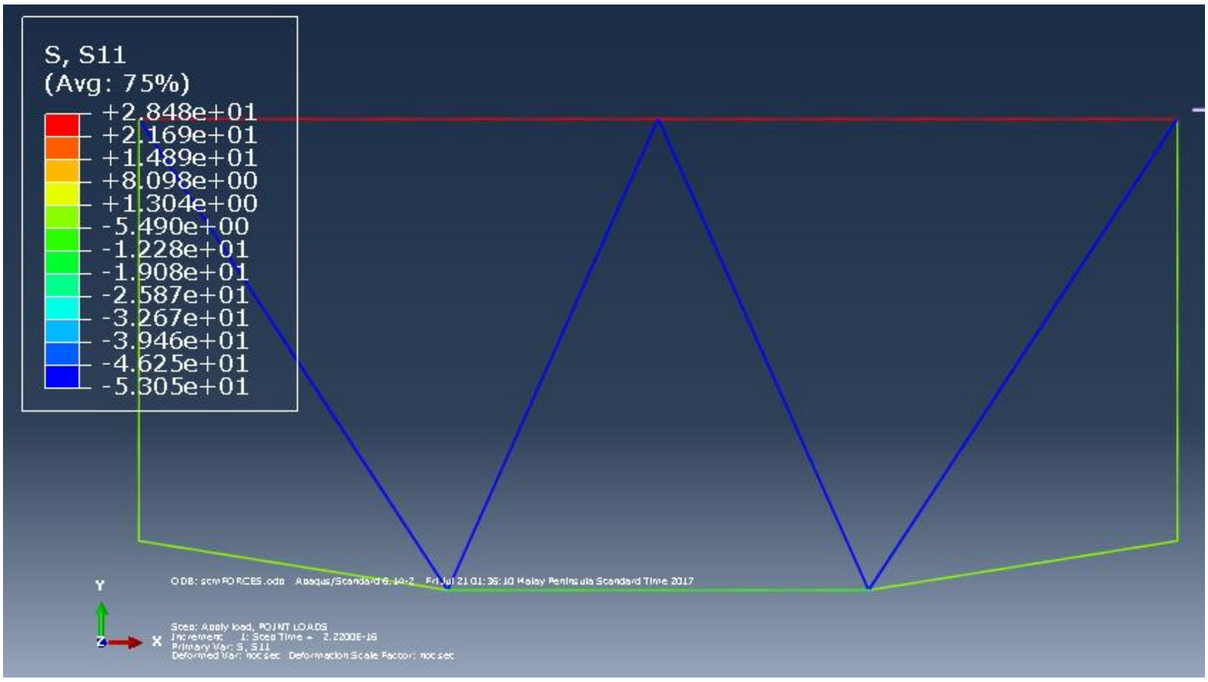

Figure 4. Member stress

F. *Tie sizes*

From the finite element results obtained that ties and strut 1, 2 and 4 are the most critical. Apparently, reinforcing steel for these cases are considered and designed as following;

$$A_{st} \geq \frac{P_n}{f_{yd}}$$

Where;

$$f_{yd} = \frac{f_{yk}}{1.15}$$

Ties 1 and 2

Pn= 3,336 N, f_{yk} = 460 N/mm2

;- $f_{yd} = 400$
Ast ≥ 3336/460
=8.34 mm
Ast ≥ 220mm^2
For T12 bars at 200; required area of steel = 337mm^2 specified in the case study bridge is far greater than 8.34 mm^2

G. Stresses in struts and Nodal zones

Node dimensions are obtained by considering vehicle wheel contact area of Eurocode, which is 400mm×400mm from load model 1 tandem system. Crucial struts and their corresponding nodes are analysed as follows:-

1) Region of transverse compression

$$\sigma_{Rd,max} = f_{cd}$$

But,

$$f_{cd} = 0.85 f_{ck}/1.5$$

= 0.85× 50/1.5 (For concrete grade 50)

;- $\sigma_{Rd,max}$= 28.5N/mm^2
Strut 4
Pu= -3.34 kN
Area = 400mm×10mm;
Stress = 0.834 N/mm^2 ≤ 28.5N/mm^2, so it is ok.

2) Region of transverse tension

$$\sigma_{Rd,max} = 0.6 v' f_{cd}$$

Where, $v' = 1\text{-}fck/250$

; - $\sigma_{Rd,max}$= 13.6N/mm^2
Struts 4 and 2
Area = 400mm×100mm;
Stress = 0.1 N/mm^2 ≤ 13.6N/mm^2, so it is ok.

III. Conclusion

In this paper, an analysis of an existing case study slab-on-girder bridge was carried out using strut and tie model; Following conclusions from the findings can be made;-

- Steel reinforcement required from the Strut-and-tie model do not exceed the shear reinforcement provided in the case study bridge design.
- The critical compressive stresses of the struts in the model do not exceed the limiting strengths which indicate the suitability of the method.
- The strut-and-tie model elements consisting of concrete compression strut and steel reinforcement ties used solely withstand the bridge loading without any contribution of transverse steel reinforcement of the slab deck.
- The concrete beam girder web and flange stiffness contributed substantially on the carrying capacity of the top slab. This behaviour would immensely reduce the use of high amount of transverse reinforcing steel in the slab deck.

Acknowledgement

The authors thank the Malaysian Ministry of Higher Education (MOHE) and Universiti Teknologi Malaysia (UTM) for research grant (O.J130000.2522.10H55) and facilities. The authors also thank the Center for Information and Communication Technology (CICT) in Universiti Teknologi Malaysia for supporting and providing facilities and services of high performance computing. The first author also appreciates the support of Kano University of Science and Technology Wudil and Tertiary Education Trust Fund (TETFUND) Nigeria.

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