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Simple Analysis of Tube Frame System of Tall Building by Using of Deformation Functions

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Abstract: According to increase of population in cities, tall buildings have been become interesting and fascinating for urban managers and engineers. Tubular frame structure is one of the most efficient systems in tall buildings under lateral load. The analysis of these structures usually involves considerable time and effort due to large number of members and joints. Several methods for evaluating shear lag and estimating stress of frame elements are presented recently. According to one of these methods, tube frame is assumed as a web and flange panel and then by considering deformation functions for web and flange frames and writing their stress relations as well as use of minimum energy basis, functions are presented for lateral and vertical displacement of the structure. Two relation groups suggested in this paper are capable of considering shear lag both in flange and web frames in the base of frame. The simplicity and accuracy of the proposed method is demonstrated through the numerical analysis of several structures. In addition, the results of these proposed deformation functions are compared to previous relations considered by other researchers to find the best relations.

Key words: Tube frame, Tall building, Lateral load, Shear lag, Simple analysis, Axial stress

INTRODUCTION

Due to increase of building high-rise structures, Tube frame structures are widely used as an economical system for high-rise buildings (Coull, A. and N.K. Subedi, 1971; Foutch, D.A. and P.C. Chang, 1982). In its basic form, the system consists of closely spaced exterior columns along the periphery interconnected by deep spandrel beams of each floor level. This produces a system of rigidly jointed orthogonal frame panels forming a rectangular tube which acts as a cantilever hollow box. Framed tube acts like a hollow boxed beam under lateral loads such as wind and earthquake. The occurance of shear lag has long been recognized in hollow box girder as well as in tubular buildings. The most existing exact method of analyzing (3-D software) is very expensive due to modeling and the large number of degree of freedom. In tubular buildings, flexibility of spandrel beams produces shear lag phenomenon with the effect of increasing the axial stresses in the corner columns and of reducing axial stress in the columns toward the center of flange panel of the orthogonal frame in the bottom of structure (Fig.1). Therefore, A large number of approximate methods have been carried out to investigate the behavior, deflection, vibration and modification of the stress distribution in framed tube system subjected to the lateral loads using different models (Coull and Subedi, 1971; Coull and Bose, 1975; Coull and Ahmed, 1978; Connor and Pouangare, 1991; Kwan, 1994; Lee and Loo, 2001; Mahjoub, R., et al., 2011; Tarjan and Kollar, 2004; Kaviani *et al.*, 2008). Approximated methods suggested which are useful in primary design and stress estimation of the structure. Different methods of simulation which consider elastic behaviors of perimeter frames as equivalent membranes were presented (Chan, P.C.K., 1974; Coull, A. and A.A. Ahmed, 1978; Coull, A. and B. Bose, 1975; Coull, A. and B. Bose, 1976; Ha, K.H., 1978; Kang-Kun, L., 2001; Mahjoub, R. et al., 2011). Deformations which are related to shear lag may have improper influence on unloaded members of the structure. Torsion in panel of each story may intensify existing deformations and stresses. This intensification threatens safety and stability of the structure. In this paper by considering separate deformation functions for

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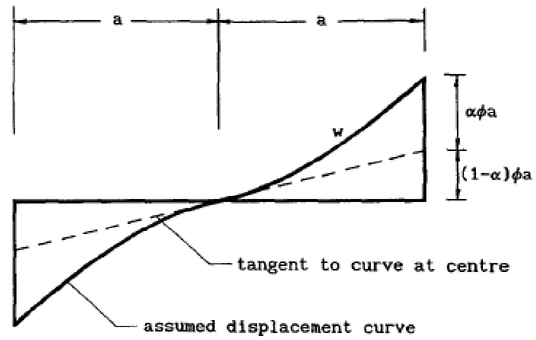
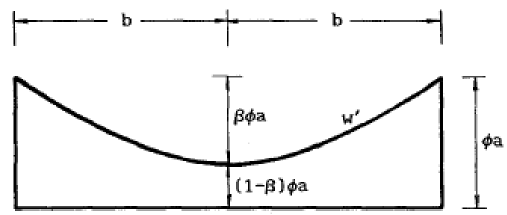
web and flange frames and then writing stress-deformations relations as well as the use of minimum energy basis, functions are suggested for lateral and vertical displacements.



(a) Web panel



(b) Flange panel

Fig. 1: Distribution of axial stress in framed tube structure (Kwan, A.K.H., 1994).

Modeling Method:

Modeling method for frame panels is carried out as orthotropic equivalent members in a way that perimeter frame could be analyzed as a continuous structure. Perimeter frame structure shown in Figure 2 can be considered as two web panels which are parallel to lateral loads direction and two flange frames which are orthogonal to that in accordance with the following assumptions: (1) with regards to the stiffness of floors, out of plane behaviors are negligible in comparison with in-plane behaviors of frames; (2) beams and columns dimensions are similar; (3) four individual columns at corners, so that frame panel can be modeled as continuous equivalent membranes (Kwan, A.K.H., 1994).

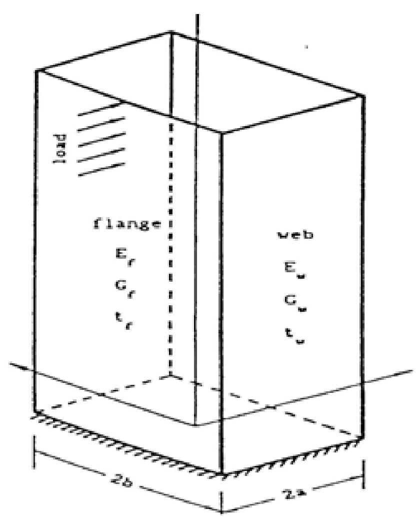


Fig. 2: Typical orthotropic panels of framed tube structure.

Mathematical Deformation Functions:

Stress distributions may not be linear in the members due to the shear lag occurs in web and flange panels. In this part, two groups of deformation functions are suggested. Therefore, the intensity of axial stresses in web depends on the intensity of axial load in flange. Axial deformations in web (W_w) and flange (W_f) can be represented by the following equations. Although Kwan, A.K.H., 1994 considered Eq. 1 and 2 in his effort but two groups of relations are proposed in this document to find the compatible equations with structure behavior. Group 1 relations are shown as Eq. 3 and 4 and group 2 relations are shown as Eq. 5 and 6.

$$W = \varphi\alpha\left[(1-\alpha)\frac{x}{a} + \alpha(\frac{x}{a})^3\right] \tag{1}$$

$$W' = \varphi\alpha\left[(1-\beta) + \beta(\frac{y}{b})^2\right] \tag{2}$$

Group1:
$$\begin{cases} W_w = \varphi\alpha\left[(1-2\alpha)\frac{x}{a} + \alpha\left(\frac{x}{a}\right)^3 + \alpha\left(\frac{x}{a}\right)^5\right] & \textbf{(3)} \\ W_f = \varphi\alpha\left[(1-2\beta) + \beta\left(\frac{y}{b}\right)^2 + \beta\left(\frac{y}{b}\right)^4\right] & \textbf{(4)} \end{cases}$$

Group 2:
$$\begin{cases} W_w = \varphi\alpha\left[(1-\alpha)\frac{x}{a} + \alpha\left(\frac{x}{a}\right)^5\right] & \textbf{(5)} \\ W_f = \varphi\alpha\left[(1-\beta) + \beta\left(\frac{y}{b}\right)^4\right] & \textbf{(6)} \end{cases}$$

Where $\emptyset$ is the rotation of plane section which connects four sides of tubular structure which were originally in a horizontal plane. α and β are dimensionless coefficients of shear lag which show degrees of shear lag in web and flange planes. Relations for section rotation ($\emptyset$), axial and shear strains in web and flange planes are given by the following equations respectively:

$$\phi = \frac{1}{EI}\int_0^z M\,dz \tag{7}$$

$$\varepsilon_z = \frac{\partial W_w}{\partial z}, \quad \varepsilon'_z = \frac{\partial W_f}{\partial z} \tag{8}$$

$$\gamma_{xz} = \frac{\partial u}{\partial z} + \frac{\partial W_w}{\partial x}, \quad \gamma_{yz} = \frac{\partial W_f}{\partial y} \tag{9}$$

The strain energy of perimeter frame is calculated as follows:

$$\Pi_e = \int_0^h \int_{-a}^{a} t_w(E\varepsilon_z^2 + G\gamma_{xz}^2)dx\,dz + \int_0^h \int_{-b}^{b} t_f\left(E\varepsilon_z'^2 + G\gamma_{yz}^2\right)dy\,dz \tag{10}$$

The potential energy of the applied lateral load is given by the following equations for different load cases:

Case 1: Single load **P** at the top of the structure:

$$\Pi_p = Pu(h) \tag{11}$$

Case 2: Uniformly distributed load with **P** defined as the intensity of load per unit height:

$$\Pi_p = -\int_0^h Pu(z)\,dz \tag{12}$$

Case 3: Linearly distributed load (triangular) with **T** defined as the intensity of load per unit height at top and zero intensity at the bottom:

$$\Pi_p = \int_0^h T\frac{z}{h}u(z)\,dz \tag{13}$$

Where u is the lateral displacement of the structure which can be calculated by Equation 14 while **S** is the shear force of lateral load. Coefficients α and β in group 1 and group 2 equations are assigned with the use of minimum energy basis which are shown in table 1 and table 2 respectively.

$$u = \int_0^z \left(\frac{S}{4G_w t_w a} - \varphi \right) dz \tag{14}$$

The value of parameters mentioned in table 1 and 2 are given in equation 15 to 21.

$$B = \frac{b^2}{a^2}E_f; \quad A = \frac{a^2}{h^2}E_w; \quad H = \frac{z}{h} \tag{15}$$

$$C_{1P} = H^2 - 3H + 3 \tag{16}$$

$$C_{1U} = H^4 - 5H^3 + 10H^2 - 10H + 5 \tag{17}$$

$$C_{2U} = H^6 + -7H^5 + 21H^4 - 35H^3 + 35H^2 - 21H + 7 \tag{18}$$

$$C_{1T} = 5H^6 - 42H^4 + 35H^3 + 105H^2 - 210H + 140 \tag{19}$$

$$C_{2T} = 21H^4 - 5H^6 \tag{20}$$

$$C_{3T} = H^8 + 24H^5 - 216H^3 + 192H^2 \tag{21}$$

Table 1: Group 1 coefficients

Load Case	α	β
Single load at top	$\frac{561AC_{1P}}{7240AC_{1P}+12639G_wH^3(H-5)+84260G_wH^2}$	$\frac{693BC_{1P}}{3880BC_{1P}+1611G_fH^3(H-5)+10740G_fH^2}$
Uniform load	$\frac{17671.5AC_{1U}}{22806AC_{1U}+21065G_wC_{2U}}$	$\frac{3759.5BC_{1U}}{4074BC_{1U}+895G_fC_{2U}}$
Triangular distributed load	$\frac{8078.4AC_{1T}}{52128AC_{1T}+455004G_wC_{2T}+147455G_wC_{3T}}$	$\frac{4435.2BC_{1T}}{9312BC_{1T}+19332G_fC_{2T}+6265G_fC_{3T}}$

Table 2: Group 2 coefficients

Load Case	α	β
Single load at top	$\frac{16.5AC_{1P}}{120AC_{1P}+231G_wH^3(H-5)+1540G_wH^2}$	$\frac{18.9BC_{1P}}{56BC_{1P}+27G_fH^3(H-5)+180G_fH^2}$
Uniform load	$\frac{74.25AC_{1U}}{54AC_{1U}+55G_wC_{2U}}$	$\frac{170.9BC_{1U}}{98BC_{1U}+25G_fC_{2U}}$
Triangular distributed load	$\frac{118.8AC_{1T}}{864AC_{1T}+8316G_wC_{2T}+2695G_wC_{3T}}$	$\frac{105.8BC_{1T}}{224BC_{1T}+450G_fC_{2T}+175G_fC_{3T}}$

Where G_w and G_f are equivalent shear Modulus of web and flange panels, E_w and E_f are equivalent Young's Modulus of web and flange respectively. From these relations, it can be concluded that the shear lag coefficients in each panels depends on elastic properties of materials and the height of structure. It can be observed that shear lag coefficients increase as the dimensions of the structure (2a, 2b, H) increase.

4- Mathematic Study:

Shear lag phenomenon is observed not only in tube frames but also in cantilever boxed beams (Foutch, D.A. and P.C. Chang, 1982). Numerical method is used to calculate the variations of axial stress in web and flange panel. Stress values can be derived by applying the Hook's law:

$$\sigma_{web} = E\frac{\partial w_w}{\partial_z} \quad (22)$$

$$\sigma_{flange} = E\frac{\partial w_f}{\partial_z} \quad (23)$$

The unknowns values of α and β are derived from relations (15) to (21) and table 1 and 2 which leads to lengthy relations for stresses for group 1 and group 2 respectively. According to equations 22 and 23 and considering of equation group 1 and 2, it can be concluded that $\emptyset$ is the only parameter which depends on z. So, the values of $d\phi/dz$ are given by Equations (24), (25) and (26) for different types of loading like as: single load at top, uniform load and triangular distributed load, respectively.

$$\frac{d\phi}{dz} = \frac{M}{EI} = \frac{p(h-z)}{EI} \quad (24)$$

$$\frac{d\phi}{dz} = \frac{M}{EI} = \frac{p(h-z)^2}{2EI} \quad (25)$$

$$\frac{d\phi}{dz} = \frac{M}{EI} = \frac{T(h-z)^2}{6h}\left(\frac{z+2h}{EI}\right) \quad (26)$$

Equations 27 and 28 are defined by using the equilibrium of bending moments and axial loads in web and flange panels in order to calculate the unknown equivalent amount of EI for group 1 and 2, respectively.

$$EI = \frac{4}{3}t_wE_wa^3\left(1-\frac{34}{35}\alpha\right)+4t_fE_fa^2b\left(1-\frac{22}{15}\beta\right) \quad (27)$$

$$EI = \frac{4}{3} t_w E_w a^3 \left(1 - \frac{4}{7}\alpha\right) + 4 t_f E_f a^2 b \left(1 - \frac{4}{5}\beta\right) \quad (28)$$

5- Numerical Study:

To illustrate the application of the proposed relations, it is compared with exact and Kwan's methods by using a 60 story reinforced concrete building with the following specifications: Height of stories 3 meters, column spacing 2.4 meter, dimensions of all beams and columns 0.8 x 0.8 meter, point load at top 6500 KN, uniformly distributed load 120 KN/m, triangular distributed load (higher value) 500 KN, E=20 GPa, equivalent value of G=1.441 GPa, 2a=30 m and 2b=35 m. Figure 3 and 4 show the axial stress in flange and web panel under lateral point load at top. Due to these figures, it can be concluded that proposed relations (group 1 and 2) are more capable than Kwan's relations (1994) in estimating of axial stress in flange panel but Kwan's relations can predict the axial stress in web panel better. Figures 5 to 7 show the comparison of axial stress of proposed relations, Kwan's relation and exact method under lateral uniform and triangular load to each other.

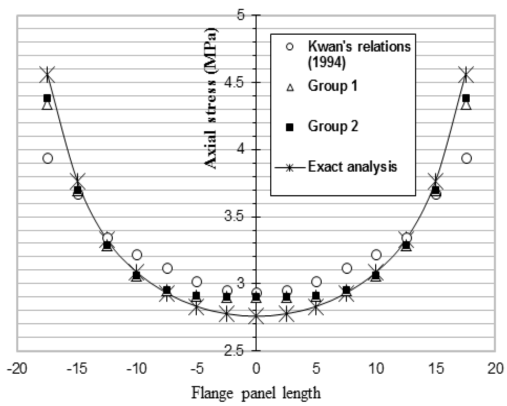


Fig. 3: Axial stress in flange panel under lateral point load.

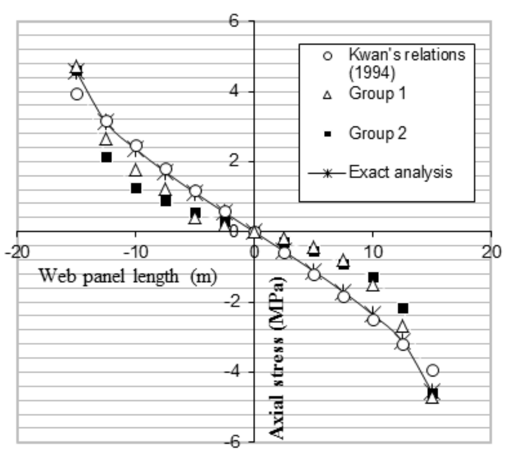


Fig. 4: Axial stress in web panel under lateral point load.

According to Figures 5 to 7, it is observed that suggested relations (group1 and 2) can consider positive shear lag effects in flange panel better than Kwan's relations. In some cases, the proposed relations perfectly able to estimate stress in columns very close to real stress calculated by exact method. On the other hand, none of the suggested relation groups and Kwan's relation cannot estimate stress in columns at the height of structure accurately. Figure 8 shows the differences between exact results and proposed relation estimations at the height of structure in story 30. In fact, there is a phenomenon named negative shear lag which occurred in the height of framed tube structure.

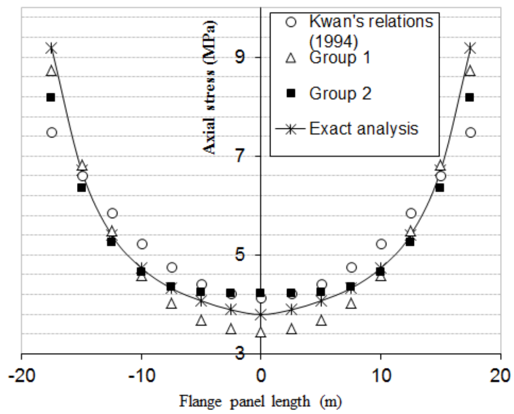


Fig. 5: Axial stress in flange panel under lateral uniform load.

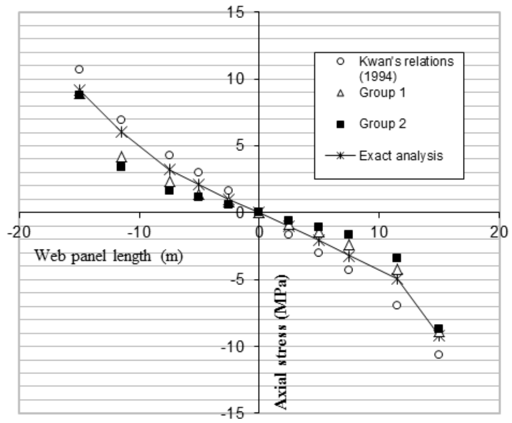


Fig. 6: Axial stress in web panel under lateral triangular distributed load.

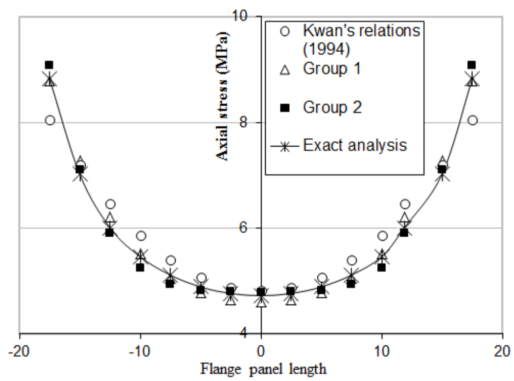


Fig. 7: Axial stress in flange panel under lateral triangular distributed load.

6- Conclusion:

The presented method in this paper is capable of explaining stress distribution with high accuracy. The following results can be obtained:

1- Stress in each column can be calculated by their coordinates.

2- The results of proposed relations are closer to exact method than Kwan's relations.

3- The use of proposed relations is harder than Kwan's simple relation and the estimations of these relations are very close to each other.

4- Proposed equations are capable considering positive shear lag at the bottom of the structure with high accuracy for both web and flange panels but they cannot estimate the stress at the height of structure because of negative shear lag effect.

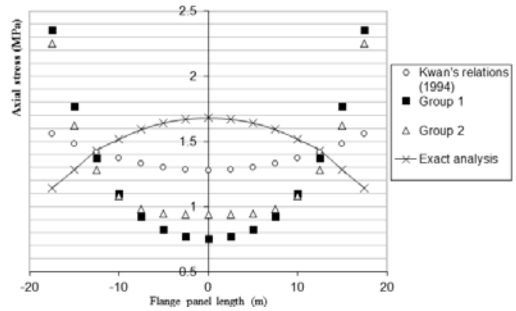


Fig. 8: Axial stress in flange panel under lateral.

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