SIMPLE MODEL FOR PRYING FORCES IN T-HANGER CONNECTIONS WITH SNUG TIGHTENED BOLTS

By

Fathy Abdelmoniem Abdelfattah
Faculty of Engineering at Shoubra,
Zagazig University, Banha Branch

Mohamed Salah A. Soliman
Faculty of Engineering at Shoubra,
Zagazig University, Banha Branch

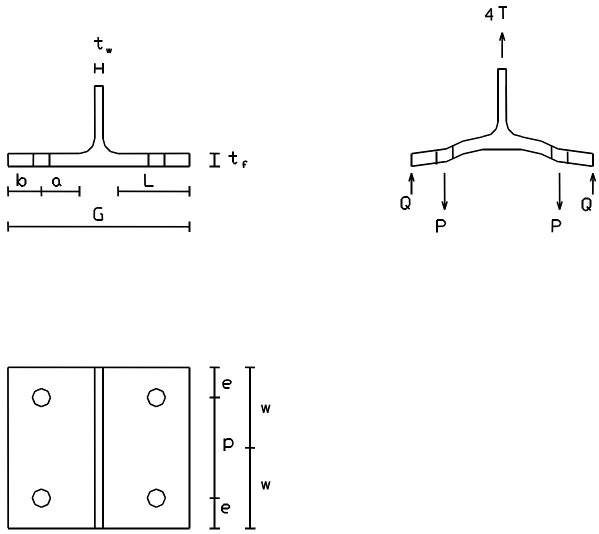
ABSTRACT
A simple model for evaluating prying forces in T - hanger connection with snug tightened bolts is proposed. The model includes the flexural stiffness of the flanges and the axial stiffness of the bolts. It is valid as far as the connection behaves in an elastic manner. Prying forces' values were obtained from this analysis and compared to those obtained from the proposed model. The obtained results show good agreement and verify the adequacy of the proposed model. A parametric study was carried out. The effects of the different geometrical properties of the connection on prying force values have been presented and discussed. Design procedure is proposed.

KEY WORDS
Connections , tension , T - hanger, prying force, bolts, snug tightened

INTRODUCTION
Hanger type connections are employed in steel structures to transmit tension forces. Four bolts are normally used in this type of connection and positioned in two rows symmetrical about the web, **Fig. 1**. Due to connection displacements and deformations, flanges may react against their base. This would induce forces at these positions called prying forces. The magnitudes of these forces depend on the flexure stiffness of the flanges and the axial stiffness of the bolts, (Faella et. al. 1998 and Fleischman et. al. 1991). The bolts are required to resist both the applied tension force and the induced prying forces.

Several relationships have been suggested in the literature to determine the magnitude of prying forces, (Douty et. al. 1965, Kato et. al. 1973 and Agerskov 1976). However, these relations were derived assuming that bolts are preloaded to their full proof loads. Prying force magnitude is related in this case to bolts' separations, bolts yielding and/or the development of the flanges plastic moment. For allowable stress design, The model provided in the 8th edition of the American Institute of Steel Construction manual (AISC 1980) can be used. This model was recommended before by (Fisher and Struik 1974). Later, this model was modified by (Astaneh 1985 and Thornton 1985) to avoid the iterative process required to obtain simpler design procedure. The two major independent failure modes considered in this model are the flanges and the bolts' failures. It is assumed that equal critical moments exit at the face of the web and at the bolt line, (AISC 1980). This moment is equal to half the plastic moment of the flange. Bolt's failure is limited by their allowable loads. The prying forces' values calculated using this model satisfy these limit conditions. The procedure in general is a limit state design method.

In this paper, The authors propose a simple model for evaluating prying forces in T - hanger connections with snug tightened bolts. The model includes the flexural stiffness of the flanges and the axial stiffness of the bolts. It is valid as far as the connection behaves in an elastic manner. The obtained values of prying forces are not affected by the change in the yield strength of the flanges material and/or the allowable load of the bolts. The finite element method was also used to model the behavior of T - hanger connections. The prying forces values were obtained from this analysis and compared to those obtained from the proposed model. A parametric study was carried out. The results are presented and discussed to indicate the effects of the different parameters on prying forces' values. Design procedure is proposed and the results are compared to those of the (AISC 1980)



(a) geometrical details. (b) deformed shape.

Fig. 1 T - hanger connections.

PROPOSED MODEL

This model is proposed for calculating prying action in T - hanger connections with snug tightened bolts. The small deflection theory is employed. Due to the symmetry about two axes, only quarter of the connection is considered. The following equations are derived for one bolt and its associated flange. The interaction behavior of the flange and its associated bolt is modeled by the structure shown in **Fig. 2**. The flange acts as a beam fixed against rotation and free to translate vertically at point C. Further, it is supported by spring against translating at point B. The active span of the beam is made equal to L.

$$L = \{ G - (2 r + t_w) \} / 2 \quad (1)$$

$$\alpha\alpha = a / L \quad (2)$$

$$\beta = b / L \quad (3)$$

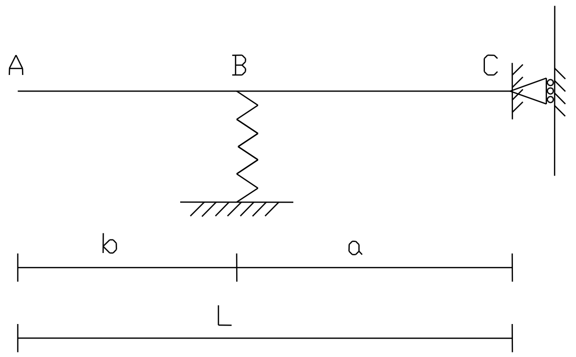


Fig. 2 Simple model for T - hanger connections.

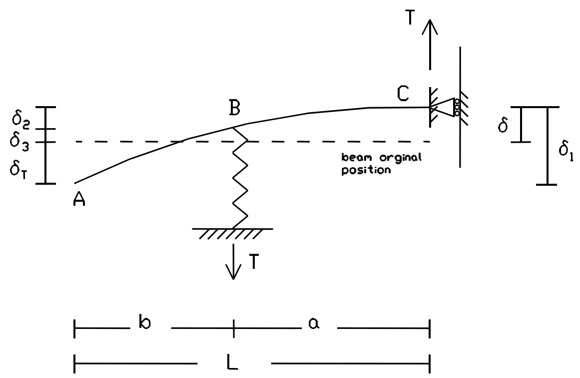


Fig. 3 Modeling the applied tension force.

Where G is the flange width, r is the fillet radius and t_w is the web thickness. The values of a and b define the position of bolt hole center. The symbols T and Q denote the applied tension force and induced prying force per bolt respectively.

When T is applied, point C translates distance δ and the spring elongates distance δ_3. The beam deforms as a cantilever, **Fig. 3**. The deflection of point A is expressed as

$$\delta_T = \delta_1 - (\delta_2 + \delta_3) \tag{4}$$

By using the deflection equation of cantilever, the following equations are obtained.

$$\delta_1 = (T\ L^3\ \alpha^2\ /\ 6\ E\ I)(3 - \alpha) \tag{5}$$

$$\delta_2 = 2\ T\ L^3\ \alpha^3\ /\ 6\ E\ I \tag{6}$$

$$I = w\ t_f^{\ 3}\ /\ 12 \tag{7}$$

and

$$\delta_3 = T\ /\ (E_b\ A_b\ /\ L_b) \tag{8}$$

Where E and E_b are the modulus of elasticity of the flange and the bolt materials respectively, w is the flange length per bolt, t_f is the flange thickness, A_b is the bolt cross sectional area and L_b is bolt grip length. When using the terms:

$$J = L^3\ /\ 6\ E\ I \tag{9}$$

$$K_b = E_b\ A_b\ /\ L_b \tag{10}$$

and applying equations (5), (6) and (8) in equation (4), the value of δ_T can be expressed as:

$$\delta_T = T \{ 3 \; J \; \alpha^2 \beta - (1 / K_b) \} \qquad (11)$$

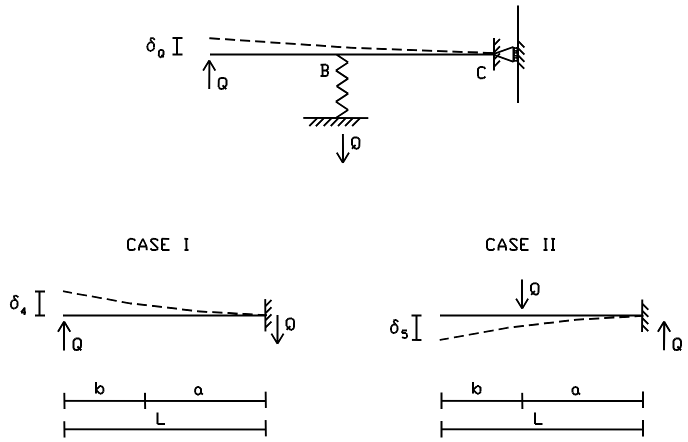


Fig. 4 Modeling the induced prying force.

Prying force is assumed to act as shown in **Fig. 4**. It is assumed that point C does not displace from its position. The problem is resolved in two cases, I and II, as shown in **Fig.4**. The spring supporting condition is not considered in this stage. The flange is dealt with as a cantilever having an active span L. The following equations are obtained:

$$\delta_4 = 2 \, Q \, L^3 / 6 \; E \; I \qquad (12)$$
$$\delta_5 = (Q \; L^3 \; \alpha^2 / 6 \; E \; I) (3 - \alpha) \qquad (13)$$
$$\delta_Q = \delta_4 - \delta_5 \qquad (14)$$

By applying equations (9), (12) and (13) in equation (14), hence

$$\delta_Q = Q \; J (2 - 3 \alpha^2 + \alpha^3) \qquad (15)$$

Returning back to the original problem, the free edge of the flange does not displace but reacts against its support. To satisfy this boundary condition, δ_T should equal δ_Q. By equating equations (11) and (15), the following equation is obtained,

$$Q / T = (3 \; J \alpha^2 \; \beta - k) / \{ J (2 - 3 \alpha^2 + \alpha^3) \} \qquad (16)$$

where $k = 1 / Kb$

This equation (16) is used to calculate prying force in T – hanger connections with snug tightened bolts.

FINITE ELEMENT METHOD

Only quarter of the connection was modeled due to its symmetry about the X - X and Y - Y axes, **Fig. 5**. This part was divided into 540 elements. Three dimensional four node quadrilateral shell elements were used. The formulation of the element is a combination of plate bending and membrane behavior. The membrane is an isoparametric formulation including transitional in-plane stiffness components and rotational stiffness components in the direction normal to the plane of the element. The plate bending behavior includes two way out-of-plane rotational stiffness and transitional stiffness components in the direction normal to the plane of the element. The flange thickness was made constant until the fillet. The thickness was then increased gradually until its attachment with the web. The material was modeled having modulus of elasticity $E = 205\ 000\ N / mm^2$ and poison ratio $\nu = 0.3$. Uniform load was applied over the web length in the positive direction of Z axis, **Fig. 5**. The bolt was modeled using 24 spring elements distributed along the perimeter of the bolt hole. They provide transitional spring support conditions having stiffness equal to the bolt axial stiffness K_b in the direction of Z axis.

Restraining Conditions

Nodes were divided into three groups. Firstly, nodes lie at the planes of symmetry. Those in the X - Z plane were restrained against rotation. Only the translation in the Z axis direction is allowed. The nodes in the Y - Z plane were allowed to rotate only about the X axis. Translation is restrained in the X axis direction. Secondly, nodes lie at the hole perimeter. These were supported by the spring elements. Thirdly, nodes lie at the flange. These nodes were required to be restrained by springs having no stiffness in tension and infinity rigid in compression. This condition was satisfied by performing the analysis into steps as follows.

Analysis Procedure

Initially, the analysis was performed while all the nodes of the third group were not restrained. The results were reviewed for negative displacements or reactions in the Z direction. These two cases violate the actual behavior of the connection. The restraining conditions of the nodes satisfying these two cases were modified. The translation in Z direction was restrained in the first case and allowed in the second one. The analysis was performed again with the new restraining conditions. This procedure of analyzing, reviewing the results and then modifying the restraining conditions of the nodes was continued until non of the results violate the actual behavior. At this state, the reactions of the springs were calculated. They should equal the summation of the applied force and the induced prying force. Prying force is evaluated by adding the reactions induced at the nodes of the third group that were supported against translation in the Z direction. The obtained results from the finite element analysis are presented in **Table 1** for different connections with different geometrical details. **Fig. 6** shows connection C 1 of **Table 1** after deformation.

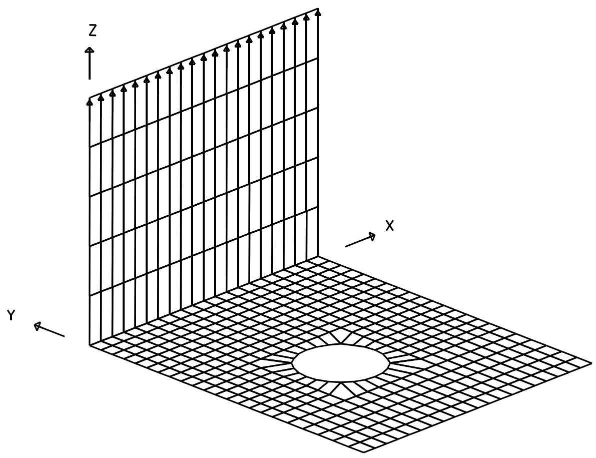


Fig. 5 Finite element mesh.

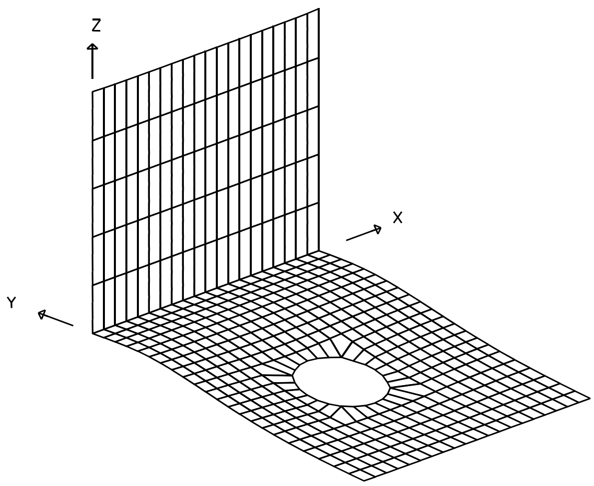


Fig. 6 Finite element result - deformation of connection C1 of table 1.

COMPARISON OF THE RESULTS

Fig. 7 compares between the results obtained from the finite element method and the proposed model. The problems dealt with in this figure have constant value of α = 0.52. The results show good agreement up to J / k = 10. After this value, the proposed model provides conservative values for Q / T but within an acceptable margin. The consistency of the agreement between the results is examined for other values of the different parameters. Connections having different geometrical properties a , b, L, $t_{f,\ \alpha,\ \beta}$ and ϕ have been studied using both the finite element method and the proposed model, **Table 1**. The obtained results confirm the agreement observed before in **Fig. 7**. The maximum difference noted is 17% in C9 at J / k = 58.4 . The comparisons in general verify the adequacy of the proposed model.

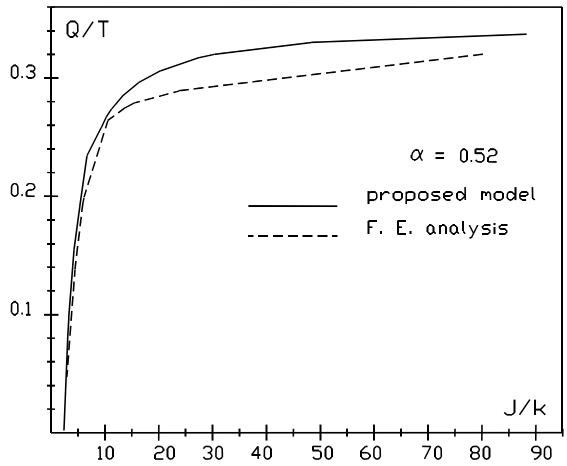


Fig. 7 Comparison between the results of the finite element analysis and the proposed model.

Table 1: Values of prying forces obtained from finite element analysis
and the proposed model:

Connection details									**Prying force ratio R = Q/T**			
Name	**a**	**b**	**L**	**t_f**	**α**	**β**	**ϕ**	**J/k**	**$R_{F.E.}$**	**R_m**	**$R_m/R_{F.E.}$**	**Notes**
C_1	30	33	63	12.7	0.476	0.523	16	15.4	0.194	0.203	105	IPE 360
C_2	30	25	55	12.7	0.545	0.454	16	10.2	0.232	0.242	104	
C_3	30	25	55	12.7	0.545	0.454	12	5.3	0.163	0.172	105	
C_4	30	20	50	12.7	0.600	0.400	16	7.7	0.250	0.265	106	
C_5	30	20	50	12.7	0.600	0.400	12	4.0	0.141	0.161	114	
C_6	30	27	57	10.7	0.526	0.474	16	19.8	0.232	0.259	112	IPE 300
C_7	30	27	57	10.7	0.526	0.474	12	10.3	0.211	0.224	106	
C_8	30	19	49	10.2	0.612	0.388	16	14.7	0.295	0.332	113	IPE 270
C_9	30	42	72	9.5	0.416	0.583	16	58.4	0.157	0.184	117	IPBI 180

PARAMETERIC STUDY

The proposed model was used to study the effect of the different parameters on prying action. The results are presented in non dimensional forms. **Fig. 8** shows the relations between Q / T, J / k and α . The value of Q / T is significantly effected by the values of J / k. This applies up to J / K = 20. After this value, the increase in J / k value does not cause significant increase in Q / T. However, the effect of α on the values of Q / T is noticeable for the different values of J / k. This indicates the importance of bolts position.

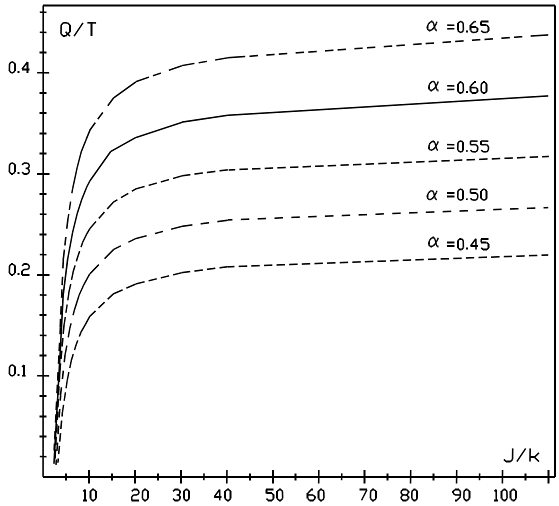


Fig. 8 Relations of Q/T , J/k and α.

Figs. 9 and **10** show the relations between Q / T , α , t_f / ϕ and w / ϕ. The following relations were used to obtain these results.

$$w = (2 e + p) / 2 \qquad (17)$$

Where e = edge distance = 1.5 ϕ
p = bolt pitch = 3.0 ϕ in figure 9 and 6.0 ϕ in figure 10 .

The axial stiffness of two bolts is given by K = 1.6 E A_b / L_b in (" Eurocode 3" 1997). The factor 1.6 accounts for the influence of prying forces, (Faella 1998). In this study, bolt axial stiffness is calculated by equation (10). The value of E_b is made equal to that of E. The value of L_b is calculated as follows :

$$L_b = t_f + R + h \qquad (18)$$

Where R is the thickness of the washers and the rigid base to which the flange is connected. It is assumed to equal 1.1 ϕ. The h is equal to bolt head and nut depths. This is found equal to 1.55 ϕ for bolts of sizes up to M 22. The results show that Q / T is inversely proportional to t_f / ϕ. The increase in the value of α would increase the induced prying force. This is true up to t_f / ϕ = 1.4 and 1.2 in **Fig. 9** and **Fig. 10** respectively. **Fig. 11** shows the effect of a value for constant α. The value of a is inversely proportional to Q / T. The use of a equal to the minimum distance required for bolt installation would produce minimum value for L. This in turn would minimize the value of the flange thickness. The comparison between **Fig. 9** and

Fig. 10 show that The increase in flange length w reduces Q / T values. This becomes more noticeable for higher values of t_f / ϕ.

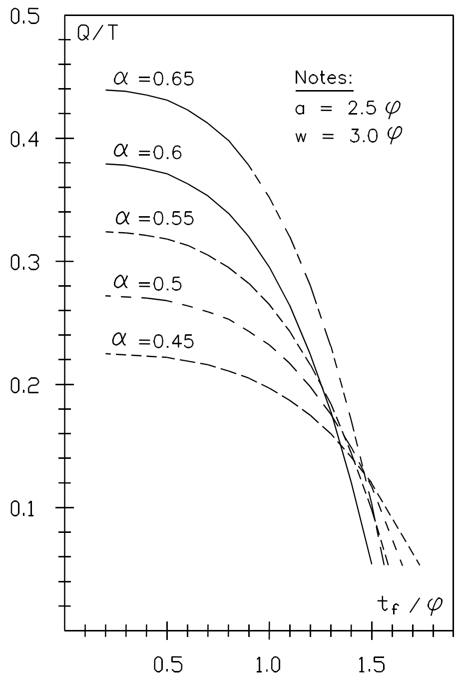


Fig. 9 Relations of Q/T , t_f /ϕ and αwhen w = 3.0 ϕ.

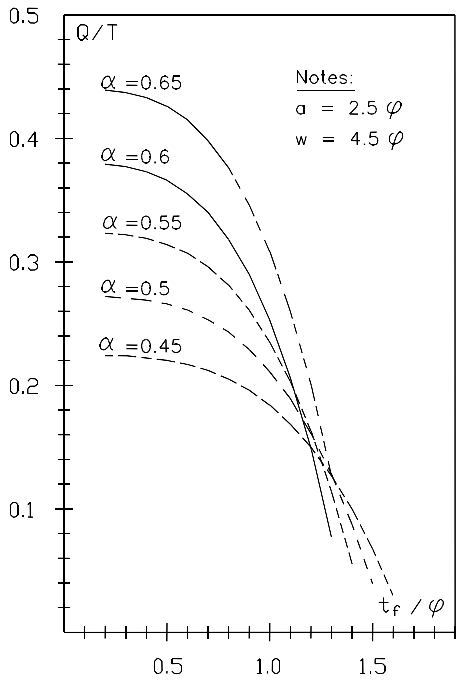


Fig. 10 Relations of Q/T , tf /ϕ and α when w = 4.5 ϕ.

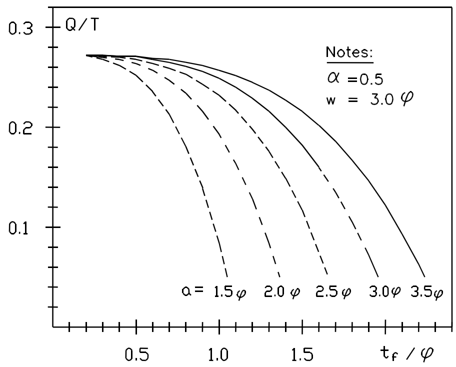


Fig. 11 Effect of a on prying forces values.

CONDITION FOR NO PRYING ACTION

When the following condition is satisfied, no prying force would induce.

$$3 \alpha^2 (1 - \alpha) = k / J \qquad (19)$$

Fig. 12 shows the relation between J / k and α when Q / T = 0.0 . The values of J / k is inversely proportional to those of α. The values of J / k are limited between 2.25 and 3 for the common values of α used in practice. **Fig. 13** and **14** show the relations between t_f / ϕ , L / ϕ and α when Q / T = 0. The following geometrical limits were used.

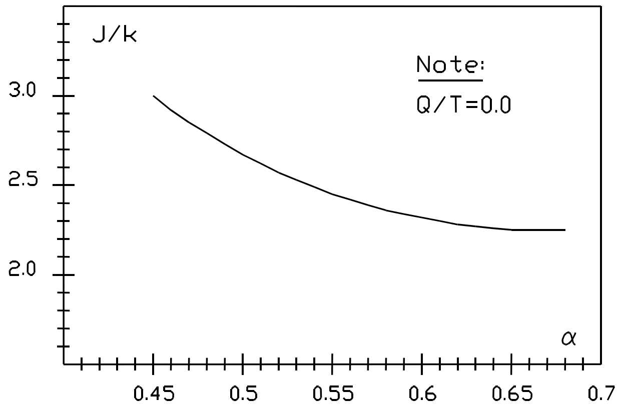


Fig. 12 Relations of J/k and α when Q/T = 0.0.

$$a \geq 1.5\ \phi \qquad (20)$$
$$1.5\ a \leq b \geq 1.5\ \phi \qquad (21)$$

The results indicate the following design notes. For constant value of L, the use of small value of α would reduce the required thickness of the flange. On the other side, for constant value of t_f , the use of high value of α would reduce the required span L . The increase in w would reduce t_f .

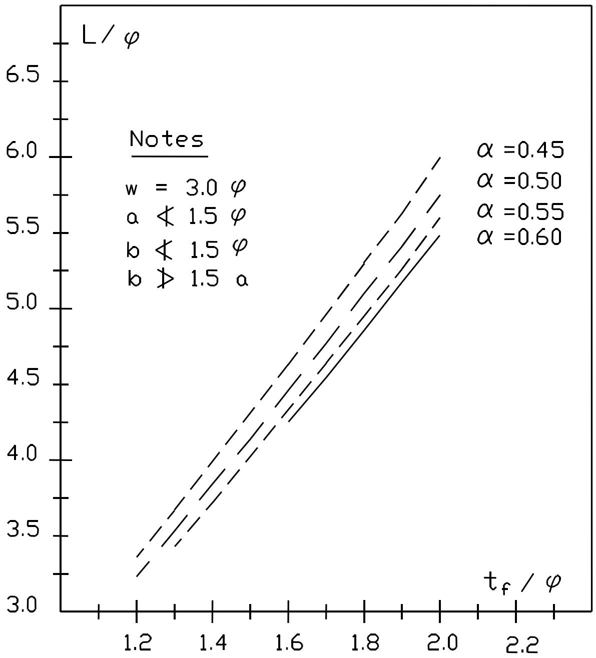


Fig 13 Relations of L/ϕ, t_f / ϕ and α when w = 3.0 ϕ.

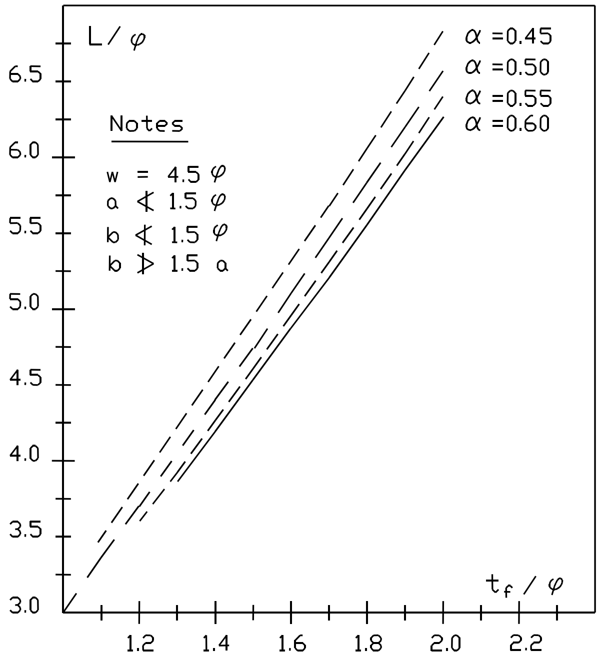


Fig 14 Relations of L/ϕ , t_f / ϕ and α when w = 4.5 ϕ.

PROPOSED DESIGN PROCEDURE

This is a working load method.

1- Assume that Q / T = 20 %

2- Load per bolt = P_i = applied tension load * 1.2 /4

3- Define bolt diameter and grade so that :
load per bolt / allowable bolt load < = 1

4- The values of a and w are dictated by installation requirements. Otherwise, it is better to reduce a and increase w as far as the specifications allow.

5- The value of t_f and L can be chosen according to the geometrical dimensions of the available sections.

6- The use of **Fig. 9** and **Fig. 10** would make the proportion of the different elements of the connection easier. However, their limitations should be satisfied. Similar figures can be obtained for other limits. The intersection of the perpendiculars at Q / T = 0.2 and T_f / ϕ value would define the required α

7- When $L > (a / \alpha)$, the following can be made:

i - reduce the value of t_f / ϕ .

ii- obtain the actual value of Q / T at these conditions and hence the value of P_f. The difference between P_i and P_f is considered as a reserve strength in the bolt.

8- The flange is treated as a cantilever having a span L and subjected to concentrated loads P_f and Q at points B and A respectively. The stresses at the end of the span should not exceed the allowable stresses in the codes.

When considering the case of design for no prying forces, the above steps are applied. However, P = applied tension force / 4. **Figs. 13** and **14** are used. The intersection of the perpendiculars at t_f / ϕ and L / ϕ would define the requiered value of α.

Example

Consider the T – hanger connection designed in example 11 –1 in the manual of the (AISC 1980). The prying force is calculated using the proposed model and compared to the value presented in the manual. The available data are:

T = 90 KN

G = 181.0 mm, t_f = 18.2 mm, t_w = 10. 9 mm, w = 100.0 mm

ϕ = 20.0 mm, R = 22.2 mm + 6 mm

The distance between the bolts center to center = 100.0 mm

Solution

By assuming that r = 12.5 mm , h = 30 mm and E = E_b

$$b = \frac{181 - 100}{2} = 40.5mm$$

$$a = \frac{100 - (10.9 + 12.5 * 2)}{2} = 32mm$$

L = a + b = 72.5 mm

Then : α = 0.441 & β= 0.559

From equation (9), (10), (18) L_b = 18.2 + 22.2 + 30 = 76.4 mm, j/k = 5.20

By using the values of α, β and j/k in equation (16)

$$Q/T = \{3\,(0.441)^2\,(0.559) - (5.2)^{-1}\} / \{2 - 3\,(0.441)^2 + (0.441)^3\} = 0.09$$

Hence Q = 8.1 KN. The value presented in the manual of (AISC 1980) is Q = 10.7 KN. The difference in Q values refers to the different assumptions used.

CONCLUSION

A simple model for evaluating prying forces in T - hanger connections with snug tightened bolts is proposed. The model includes all the parameters that affect the flexural stiffness of the flanges and the axial stiffness of the bolts. It is valid as far as the connection behaves in an elastic manner. The finite element method was also used to model the behaviour of T - hanger connections. The prying forces' values obtained from the finite element analysis were compared to those from the proposed model. The results show good agreement and verify the adequacy of the proposed model. The ratio of the flange flexural stiffness to bolt axial stiffness affects the magnitude of prying forces. The increase in the value of this ratio would reduce the induced prying forces values. This can be carryout by increasing the flange thickness and length and/or reducing the flange span. Bolts position is another significant factor that affecting prying forces values. When using the distance between bolt hole centre and the web equal to the minimum distance required for bolt installation, minimum prying force would induce. Design procedure is proposed.

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NOMENCLATURE

A_b	bolt cross sectional area.
a,b	distances define the position of bolts holes in the flanges.
E	modulus of elasticity of the flange material.
E_b	modulus of elasticity of the bolts material.
e	edge distance.
G	flange width.
h	depths of bolt head and nut.
K, K_b	bolts axial stiffness
L	flange span.
L_b	bolt grip length.
P	total applied tension load.
p	bolt pitch
Q	prying force
R	thickness of washers and rigid base.
r	fillet radius.
T	applied tension force per bolt.
t_f	flange thickness.
t_w	web thickness.
w	flange length per bolt.
α, β	ratios.
δ_1, δ_2, δ_T	deflections due to applied tension load.
δ_3	spring elongation.
δ_4, δ_5, δ_Q	deflections due to induced prying force.
ϕ	bolt diameter.
ν	poison ratio.