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FORCED ELASTIC DISPLACEMENT AT THE BEARINGS OF STATICALLY INDETERMINATE FRAMED STEEL STRUCTURES

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ABSRACT: One of the trends of technical advance in the field of construction, which insures a higher level of engineering, is the optimum use of structural materials in building structures. The principal concept of the present study is to enhance the efficiency of the framed steel structures by applying the pre-stressing concept to increase the load carrying capacity. One should not overlook the fact that the traditional means of pre-stressing often entails additional consumption of high price materials for auxiliary components (tendons, anchors, …. etc).
The present study will follow untraditional means of pre-stressing which will reduce both the cost and effort. A proposed method will be applied using the forced elastic displacement of the bearings of framed steel structures during the erection phase or even it may be successfully used to reinforce structures already in service through the redistribution of the pre-stressing moments to obtain stresses of the sign opposite to that from the dead load. When applying this method it is possible to enhance the load bearing capacity and to have lesser final strains, which will reduce the final deflection.

INTRODUCTION

Frames, arches, suspended and three dimensional systems are generally used in steel structures where the dead weight accounts for substantial part of the loads affecting these structures.

The principal concept underlying the present study is to apply the pre-stressing concept to improve the bearing capacity of the structure using a very simple technique. The proposed method may be applied to the design of new steel structures or used in the strengthening and rehabilitation of the existing structures. The proposed method is particularly important for long span roofs or heavy load structures. The study also will discuss the practical applications for different structures.

BASIC CONCEPTS FOR PRE-STRESSING OF METAL STRUCTURES

The use of pre-stressing concept to enhance the efficiency of the structures has been used long time ago. This concept has been used extensively for concrete structures. The main purpose for pre-stressing of concrete structures is to overcome the tensile deficiencies of the material. The concept of pre-stressing is extended to be used for steel elements. The main purpose for pre-stressing in this case is to create initial stresses to counteract the stresses caused by external service loads.

The pre-stressing of a steel element can be achieved by applying the traditional means, which is the use of high strength steel cables to create the preliminary pre-stressing force. This system is too expensive which may reduce the technical feasibility of pre-stressing. One should not overlook the fact that the gain from the pre-stressing process should exceed its costs. This simple fact may decrease the use of the traditional concept of pre-stressing in metal structures. The additional consumption of high price materials for auxiliary components used for the traditional pre-stressing technique (tendons, anchors, etc.) decreases the practicality of applying this method. In a study made by Regan and Krahl (1967), it showed that for working stress the use of high strength cables for pre-stressing of steel beams is not effective compared with the addition of cover plates for these beams. The reason for this is that pre-stressing in this case does not appreciably increase the moment of inertia of the cross-section because of the small tendons area compared to the area of the cover plates and also due to the fact that the use of tendons is much more expensive.

In the present study, it is found that developing a new technique of providing pre-stressing for metal elements fulfilling the economic considerations and practical applications will be of great importance to the steel designers.

THE NEW TECHNIQUE EXPLANATION FOR PRE-STRESSING OF METAL STRUCTURES

The present study explain a simple technique using the pre-stressing concept to improve the structural properties of the steel structures. This can be achieved by providing stresses opposite to that from the design loads to increase the load bearing capacity. The mechanism of this technique will be achieved using the permanent jacking concept to produce the initial pre-stressing stresses that will counteract the service load applied stresses. The use of hydraulic jacks in this method is not recommended due to the fact that they are relatively expensive; they have limited loading capacities and need regular maintenance. In this study the concept of screw jacking will be used to produce a connection that can be implemented as a permanent jack to overcome the hydraulic jacking deficiencies. The main steps of the proposed method will be explained as follows:

- First is to apply a forced elastic displacement at the bearing of the structure during the erection phase using the screw jack. This will produce a pre-stressing preliminary stress (σp).
- Applying the service loads, the preliminary stress σp will be cancelled and the stresses of the opposite sign within the range of the design strength (σs) are taken up.

For axially loaded elements,
the force taken up by the pre-stressed element is equal to:

$$P2 = A\ (\sigma_p + \sigma_s)$$

Where:

σ_P: Pre-stressing preliminary stresses.
σ_S: Service load applied stresses.
A: Cross-section area

This is greater than that a similar non-pre-stressed component as the force taken up by the similar non-pre-stressed element is equal to:

$$P1 = A\ \sigma s$$

It is clear from Fig. (1), that by applying a preliminary stress (σp) of the sign opposite to that of the design service load, it is possible to enhance the load bearing capacity of the element. It should also be mentioned that pre-stressing always causes initial deformations in the element which is opposite to that from the service load. Applying the service load will cancel the initial deformation first then the element will be strained in the direction of the load which may improve the structure final deformations.

MULTI STAGE PRE-STRESSING

The load bearing capacity and the rigidity of the structure may be enhanced still further by the use of multi-stage pre-stressing, in which the pre-stressing and the loading of the structures are carried in a number of steps (Fig. 2). Initially, a preliminary stress σp1 is created, and then a service load Ps1 is applied to bring the stress in the element to the limit value (R). The second step consists in providing a pre-stressing σp2 (σp2 > σp1) of the opposite sign and then applying a service load Ps2. After a number of such steps, the total service load (Ps1 + Ps2 +….) may be several times greater than the load which the structure is capable of withstanding without pre-stressing (P) as shown in Fig.(2). It should be borne in mind that the service load is to be constant in the course of multi-stage pre-stressing. If this service load acting upon the structure is removed, then the pre-stressing forces may cause damage to the structure. For this reason it is recommended to apply the pre-stressing concept to control the constant loads of the structure only.

CONCEPT OF SCREW JACKING

In the present study the concept of screw jacking is developed to produce a connection that can be implemented as a permanent jack. This connection will be part of the structure that can be used to produce the pre-stressing forces. This method is seen as a simple low cost tool that may be used. The pre-stressing force using this type of connection may be adjusted to be horizontal, vertical or even inclined to counteract the service loads.

SCREW JACK CONNECTION DESCRIPTION AND MECHANISM

The basic form of the screw jack connection detail (fig.3) consists of three main elements:

1- Bearing plate.
2- Jacking bolts.
3- Supporting pedestal.

The Bearing Plate:

The main function of the bearing plate is to reduce the effect of load concentration and to prevent the local deformation for the steel element connected to the jack.

The Jacking Bolts:

The shown model in Fig.4 indicates 4 bolts with their nuts and washers. It should be mentioned that it is recommended to use two nuts. The lower will be used as a bearing nut. The upper will be used as a lock nut and it will also be used for load adjustment.

The Supporting Pedestal

It consists of two plates, upper and lower supporting plates fillet welded to part of a steel column as shown in Fig.(3). The upper supporting plate contains 4 holes in a symmetric position around the column section and as near as possible to the column web. The height of the supporting pedestal should be the smallest height that may be used to avoid the local buckling effect.

The jack connection should be adjusted to support the base element for the structure, that is required to be initially pre-stressed as shown in Fig.(4). It is recommended to adjust the initial pre-stressing during the erection phase of the structure and before the tightening of the anchor bolts. It is also recommended to use bigger holes or even slotted holes for the anchors to allow for the elastic displacement at the bearings. After initial pre-stressing procedure is completed plate washers may be site welded to the column base plate. This procedure is particularly important to allow the initial forces to affect the structure and not to transmit the initial pre-stressing directly to the anchors.

As the design procedure will require the use of a certain value of the initial pre-stressing force, then a load indicating device should be used to determine such force. The most familiar load indicating device known to the steel specialists is the calibrated wrench indicator. This wrench is frequently used for the high strength bolts tightening for friction connections. There are different types of load indicating wrenches. The most familiar types of wrenches are:

1- Calibrated direct tension wrench.
2- Calibrated torque wrench.

These wrenches are the most appropriate devices to control the pre-stressing load.

DESIGN PHILOSOPHY AND APPLICATIONS OF THE DEVELOPED METHOD

The effectiveness of pre-stressing for structures depends to a substantial degree on the following factors:

1- The span and the loads of the structures, as the pre-stressing is effective for both large spans and heavy loads.
2- The type and shape of structures. The pre-stressing efficiency is greater for inclined and arched type structures.
3- The sequence of pre-stressing. When pre-stressing is applied in a number of steps, it is possible to increase the structure bearing capacity. This will be effective within the elastic range only.

Method of Calculation

Applying the new method for trusses calculation

First it is necessary to assume the preliminary cross-sections before pre-stressing. Then the following preferable sequence may be applied:

1- Initial pre-stressing force is applied for part of the constant service load.
2- Part of the constant service load will be applied which may include the trusses and braces own weight and, possibly, part of the roof structure.
3- Another cycle of loading after applying the first phase of pre-stressing will include the part of the roof load which is laid after the truss is placed in position.
4- The forces in the truss members due to full design load Nd; erection load Ne should be calculated.
5- Unit pre-stressing force N1 is determined.

The most stressed element in the truss is found and is taken as the critical element for both the top and bottom chords. The cross-sectional area of the critical element Acr is determined, and then the limit force in the critical element is found. The limit force in the critical element Ncr is found from its cross-sectional area (Acr)

$$Ncr = Acr\ \sigma$$

The design force in any element of the truss

$$Ni = Ndi - N1i\ Np.$$

The design force in the critical element

$$Acr\ \sigma = Ncr - N1cr\ Np.$$

Where:

Np = the pre-stressing force.
Ndi = Force in the element i of the principal system due to design load.
N1i= Force in the element i due to unit pre-stressing force.
N1cr=Force in the critical element due to unit pre-stressing force

Then the pre-stressing force

$$Np = (Ncr - Acr\ \sigma)/ N1cr.$$

Knowing the pre-stressing force Np , it is possible to determine the forces and then the cross-sectional areas for each element.

Main Formulas for Calculating Multi-stage Pre-stressing

The possible number of pre-stressing steps and the values of the pre-stress and the external design load depends to great extent on the least difference between the stresses in the chords due to service loading and pre-stressing. This coefficient is calculated from the stress difference in the element of maximum stresses in the upper and lower chords. For these elements, the coefficient of stress differences Q1 and Q2 are respectively equal to:

$$Q1 = (Nbp - Ntp)/ Nbp$$
$$Q2 = (Ntd - Nbd)/ Ntd$$

Where:

Nbp & Ntp : Forces in the respective check top and bottom chord elements due to unit forces of pre-stressing.
Ntd & Nbd : Forces in the respective check top and bottom chord elements due to unit vertical service loads.

It can be found from the previous applications that the smaller the magnitude of the coefficients Q1 & Q2, the greater the number of possible pre-stressing steps. When multi-stage pre-stressing is begun by applying a pre-stressing force X1 to a maximum pre-stressing compressive force in the bottom chord, after which a load P1 is applied, whose value is ultimate as regards the compressive stresses in the top chord. The pre-stressing and loading cycles then will repeat themselves and it is possible with the use of the previous formulas to obtain the general equations to determine the values of loading and pre-stressing forces at each stage:

$$Pi = 1/Ntd \; (Nb\; k1 + Nt) \; (k1\; k2)^{I-1}$$

$$Xi = 1/Nbd \; (Nb\; k1 + Nt) \; (k1)^{i-2} \; (k2)^{i-1}$$

Where:

-Nb & Nt = load carrying capacity in compression of the check elements of the bottom and top chords.

-X= pre-stressing force from the screw jack.

-P= vertical load value.

-k1=1-Q1= coefficient of relief of the top chord.

-k2=1-Q2= coefficient of relief of the bottom chord.

In the previous equations, “i” is ordinal number of the pre-stressing stages. The starting values of i are respectively unity and two, etc. The initial pre-stressing force :

$$X1= Nb / Nbd$$

It is clearly apparent from the previous formulas that values P and X are converging functions of coefficients K1 and K2. The greater the values of K1 and K2, the slower the convergence of P and X functions.

APPLICATION EXAMPLE FOR THE PROPOSED DESIGN METHOD

To apply the new method on an arch-type truss which will be subjected to a multi-stage pre-stressing as a demonstration example; it is necessary to assume the truss member cross sections and to determine the load carrying capacity of its elements for both compression and tension strengths (see first two columns of table 1). The unit loading for the case of pre-stressing and service loading is calculated. It is readily apparent from the table that the check members will be member g-h of the top chord and member m-n for the bottom chord in which :

Ntd = 22.6 ton Nbd = 2.39 ton.

The coefficients of relief k1 & k2

k1 = 1- Q1= 1- ((Nbp – Ntp)/ Nbp) = 1- ((2.39-1.51)/2.39) = 0.632

k2 = 1- Q2= 1- ((Ntd – Nbd)/ Ntd) = 1-((22.6 - 22)/22.6) = 0.973

To calculate the ordinate pre-stressing forces

X1= Nb / Nbd = 33.4/2.39 = 13.97 ton.

For the rest of the ordinate pre-stressing forces the following equation will be applied:

$$X_i = 1/N_{bd} (N_b k_1 + N_t) (k_1)^{i-2} (k_2)^{i-1}$$

X2= 1/2.39 (33.4*0.632 + 33.4) (1) (0.973) = 22.2 ton.

X3= 1/2.39 (33.4*0.632 + 33.4) (1) $(0.973)^2$ = 13.65 ton.

To calculate the service load intervals :

$$P_i = 1/N_{td} (N_b k_1 + N_t) (k_1 k_2)^{i-1}$$

P1 = 1/22.6 (33.4* 0.632 + 33.4) (1) = 2.41 ton.

P2= 1/22.6 (33.4* 0.632 + 33.4) (0.632* 0.973) = 2.41 ton.

P3= 1/22.6 (33.4* 0.632 + 33.4) $(0.632^* (0.973))^2$ = 0.91 ton.

From the equations it is clear that the value of P3 is increasing rapidly and it is evident that further tensioning and loading stages will be ineffective.

It can be seen from the tables that, multi-stage pre-stressing may be affected until one of the chord elements is stressed to its full maximum strength.

Figure (5) shows the relationship between the value of the pre-stressing load cycles Xi and the corresponding ordinal number i .

Figure (6) shows the relationship between the value of the applied service load cycles Pi and the corresponding ordinal number i .

It can be seen that the number of load and pre-stressing operations may be increased by decreasing the value of Pi and Xi.

The total load upon the truss joints after pre-stressing cycle operations will be equal to ΣP

In the presented example, ΣP = 2.41+1.48+0.91=4.8 ton.

The maximum service load to be carried on the truss joints, without the pre-stressing operations = 1.48 ton.

CONCLUSION

From the above, it can be concluded that the truss carrying capacity following the proposed method is increased by ([4.8-1.48]/1.48) = 2.24 times the normal capacity without pre-stressing. It is also clear that the load carrying capacity increased several times by applying multi-stage pre-stressing procedure..

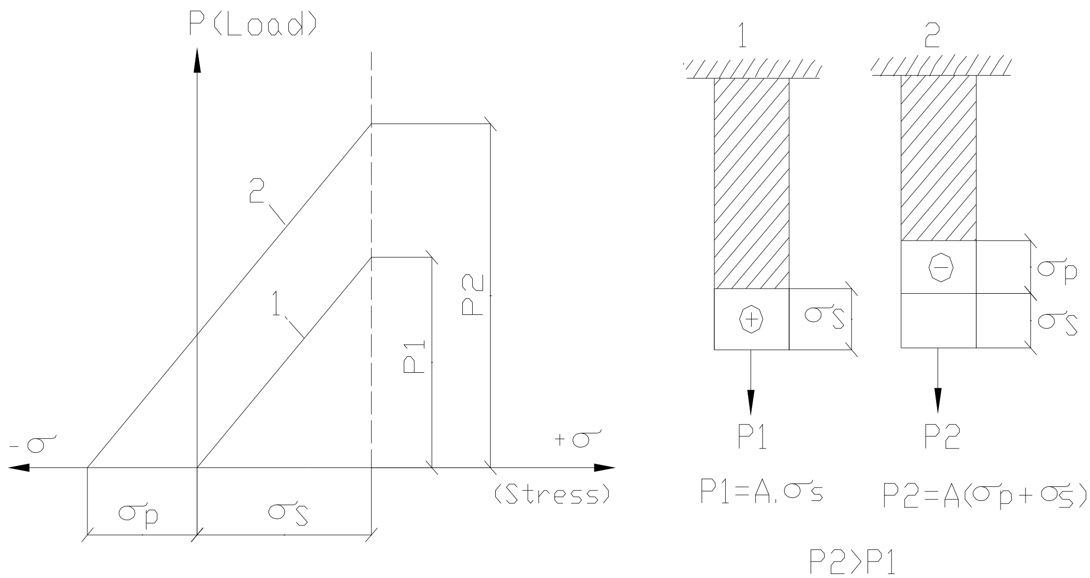

Figure 1. Enhancing the load bearing capacity of an element using the concept of pre-stressing.

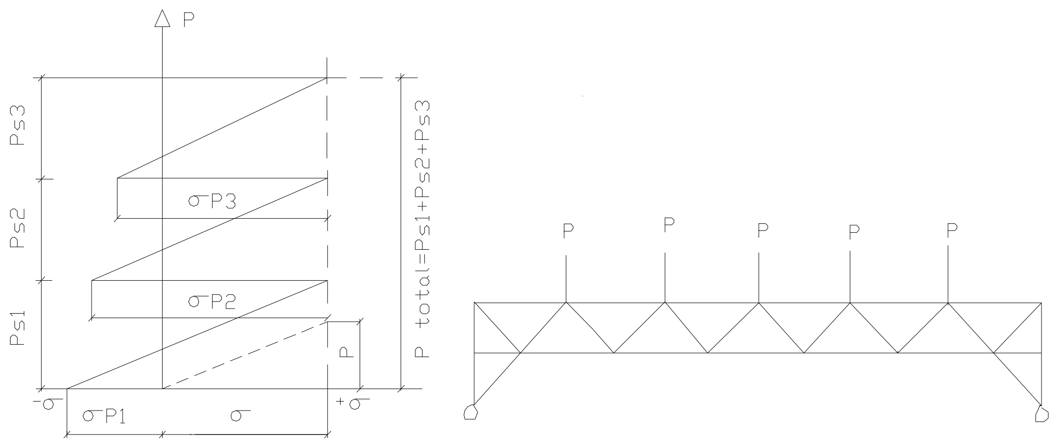

Figure 2. Increasing the load bearing capacity in multi-stage pre-stressing.

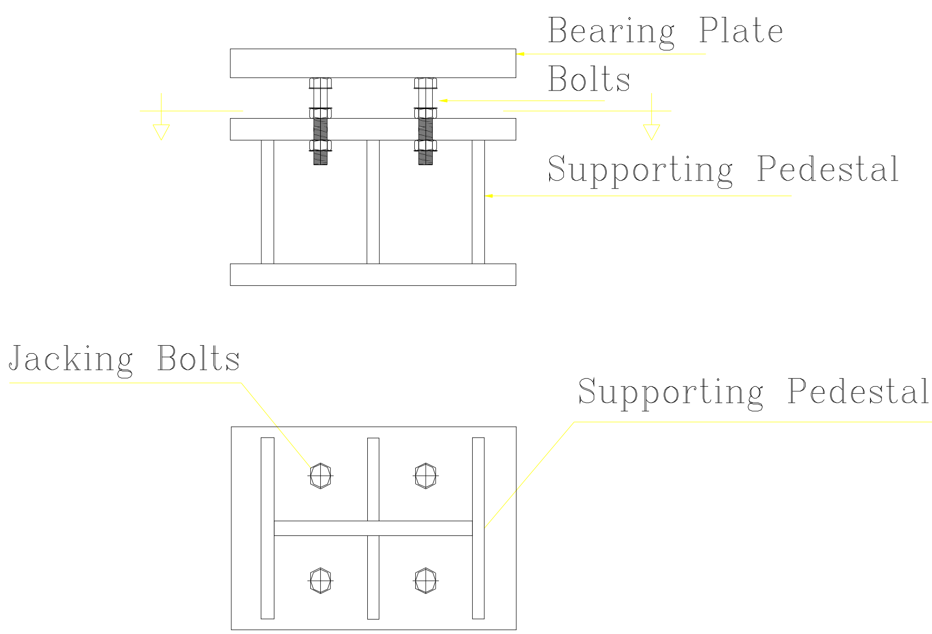

Figure 3. Screw jack components.

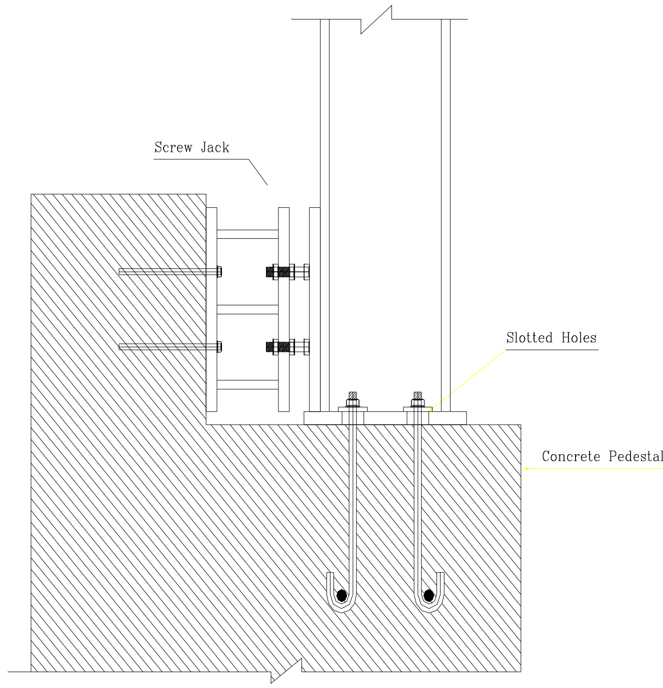

Figure 4. Screw jack connection detail

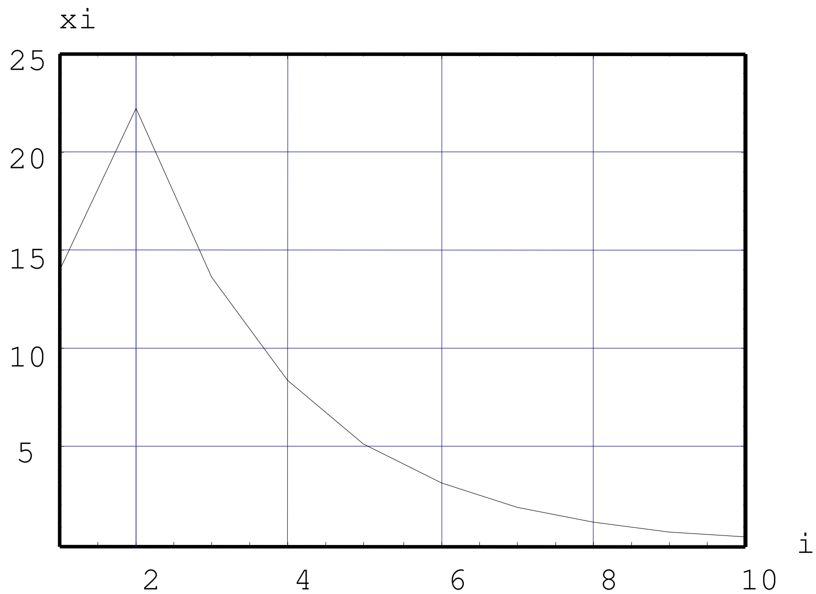

Figure 5. The relationship between the value of the pre-stressing load Xi and the corresponding ordinal number i

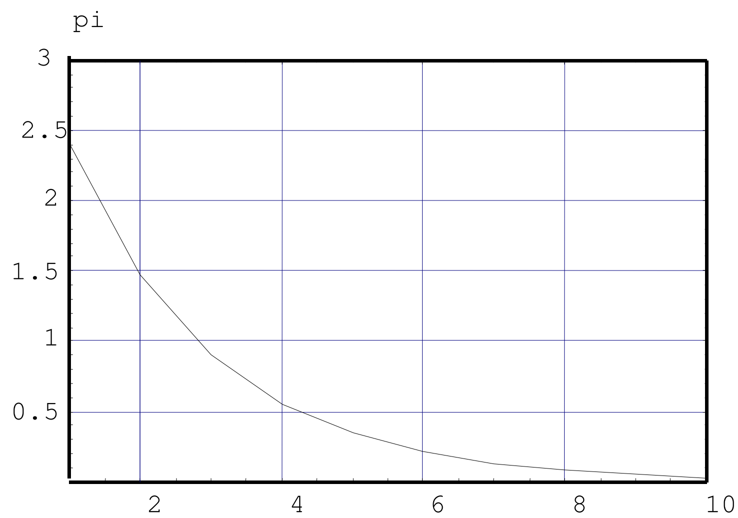

Figure 6. The relationship between the applied load Pi and the corresponding ordinal number i

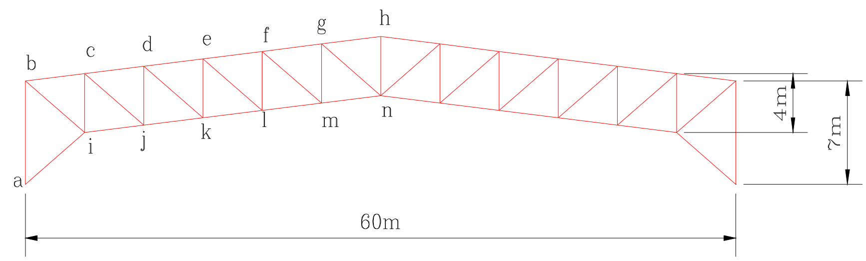

Table 1.

Truss Members		Member Capacity		Unit Forces (ton)		*Max. Forces P=1.48
Group	Member	Tension (ton)	Comp. (ton)	N=1	P =1	
Top Chord	b-c	77	-21.4	0.88	-06.90	-10.2
	c-d	77	-21.4	1.00	-12.60	-18.6
	d-e	84	-33.4	1.13	-17.00	-25.2
	e-f	84	-33.4	1.26	-20.10	-29.7
	f-g	98	-37.0	1.38	-22.00	-32.6
	g-h	84	-33.4	1.51	-22.60	-33.4
Bottom Chord	a-i	120.4	-64.5	-1.22	00.00	00.0
	i-j	120.4	-64.5	-1.88	06.90	10.2
	j-k	84	-33.4	-2.01	12.60	18.6
	k-l	84	-33.4	-2.14	17.00	25.2
	l-m	84	-33.4	-2.26	20.00	29.6
	m-n	84	-33.4	-2.39	22.00	32.6

* Maximum forces in members due to applied service load P=1.48 ton

Table 2.

Truss members		First Load Cycle			Second Load Cycle			Third Load Cycle		
Group	**Member**	**X1 =13.97**	**P1 =2.41**	**Total forces**	**X2 =22.2**	**P2 =1.48**	**Total forces**	**X3 =16.68**	**P23 =0.91**	**Final Total forces**
Top Chord	b-c	12.29	-16.63	-4.34	19.54	-10.21	4.99	12.01	-6.28	10.72
	c-d	13.97	-30.37	-16.40	22.20	-18.65	-12.85	13.65	-11.47	-10.67
	d-e	15.79	-40.97	-25.18	25.09	-25.16	-25.25	15.42	-15.47	-25.30
	e-f	17.60	-48.44	-30.84	27.97	-29.75	-32.62	17.20	-18.29	-33.71
	f-g	19.28	-53.02	-33.71	30.64	-32.56	-35.66	18.84	-20.02	-36.84
	g-h	21.10	-54.47	-33.37	33.52	-33.45	-33.30	20.61	-20.57	-33.19
Bottom Chord	a-i	-17.04	0.00	-17.04	-27.08	0.00	-44.12	-16.65	0.00	-60.77
	i-j	-26.26	16.63	-9.63	-41.74	10.21	-41.16	-25.66	6.28	-60.54
	j-k	-28.08	30.37	2.29	-44.62	18.65	-23.68	-27.43	11.47	-39.64
	k-l	-29.90	40.97	11.07	-47.51	25.16	-11.28	-298.21	15.47	-25.02
	l-m	-31.57	48.20	16.63	-50.17	29.60	-3.94	-30.85	18.20	-16.59
	m-n	-33.39	53.02	19.63	-53.06	32.56	-0.87	-32.62	20.02	-13.47

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