FEASIBILITY OF TUBULAR T-JOINTS AS A DAMAGE CONTROLLER FOR ROOF STRUCTURES UNDER LOADING

Eka Satria[1] and Shiro Kato[2]
[1]Dept. of Mechanical Engineering of Andalas University-Padang,
[2]Dept. of Civil and Architectural Engineering of Toyohashi University of Technology, Japan
email: ekasatria@ft.unand.ac.id

ABSTRACT

This paper is aimed to outline characteristics of tubular T-joints that were applied on a new type of two-way system for single layer lattice roof under influence of static and dynamics loads. The proposed roof is composed of two main arches, intersecting each other with welded T-joint struts to provide space for tensioning membranes. Two main characteristics of tubular T-joint were shown in this paper. The first is the nonlinear behaviour of the joints under repeated vertical loading and the second is under seismic horizontal loading. The interesting feature found after the first study is an ability of the system to make self-recovery after loading, since a large displacement occurred due to heavy vertical load almost vanish after unloading. While for the second study, at the strong earthquake motion, the yielding of the tubular T-joints can be used to absorb some amount of strain energy. Consequently, due to those characteristics, deformation of the arches as the main frames of the roof can be reduced and any heavy damages on the arches can be minimized.

KEY WORDS: Lattice Roof, Tubular T-Joints, Recovery System, Energy Absorber

1. INTRODUCTION

The two-way system for single layer lattice roofs is attractive to architects and engineers since such a system is beautiful in shape, light in weight and also systematic in construction. In the design steps, one of the important tasks is to secure sufficient safety against buckling. Recently, there are many accumulated researches of the stability of steel reticulated shells, however only a few of them have been developed in case of two-way system for single layer lattice roof (**Yamashita, *et al.*, 2001; Kato *et al.*, 2005, 2006; Fujibayashi, *et al.*; 2006**). Therefore, the buckling characteristics of these kinds of structures still need to be investigated.

This paper is actually an advanced study from several previous researches in investigating buckling behavior of a new type of two-way system for single layer lattice roof under vertical static loads such as snow loads (**Kato *et al.*, 2008, and Satria, *et al.*, 2008a**) and dynamic loads such as an earthquake (**Satria, *et al.*, 2008b**). The new model of roof is composed of two main arches intersecting each other with T-joint struts in order to provide a space for tensioning membranes. This system adopts no diagonal bracing elements to avoid complications in construction therefore the global form become more simpler than any previous systems.

If in the previous papers, the design feasibility of the introduced roof system under static and dynamic loads have been detailly oulined, the present paper focuses on the effect of the tubular T-joints on the overall characteristics of the roof system under loadings. The characteristic is considered very beneficial in designing of roof structures especially in areas of high seismic level.

2. NUMERICAL MODEL OF ROOF STRUCTURES

2.1. Configuration of Roof Structure

As shown in Fig.1, the roof form is in two-way model and it is composed of a set of parallel arches, where each arch is connected through a set of struts to the orthogonal arches. The surface of the roof is assumed like a curved shell, which is formed geometrically by rotating an arch of *AOB* with a radius R_z along the two same shaped arches of *EAF* and *GBH*. The radii of arches *AOB* and *COD* are R_x and R_z respectively. The total rise H is the sum of the rise, H_z, for the arch in the z direction, the length of the strut, h_t, and the diameter of the chord, D, or mathematically written as $H=H_Z+h_t+D$. The length of each member along the arches *AOB* and *COD* might be an arbitrary. In Fig.1b, several parameters are also introduced. Firstly, h_t is assumed to be constant, *2500 mm*. Secondly, l_0 is the length of arch member for each division has been assumed to be constant of *6000 mm* at the centre of the roof in x and z direction. The surface has two half open angles, ϕ_x and ϕ_z , respectively in the x and z directions. In this paper ϕ_x and ϕ_z are assumed 30^o and 25^o. Then, each arch is divided into n members, n being assumed as *10* in this study, and the total arc lengths, L_x and L_z are set just to be *60000 mm*. Therefore, both radii of arches can be calculated through equations, $R_x=n.l_{0x}/2\phi_x=57296$ *mm* and $R_z=n.l_{0z}/2\phi_z=68755$ *mm*, and the difference, $Z_0=R_z-(R_x-h_t)=13959$ *mm* using $h_t=2500$ *mm*.

2.2. T-Joint Connection

Tubular T-joint is modeled by connecting arch member, with diameter $D=318.5$ *mm* and thickness $T=8$ *mm*, to strut member, with diameter $d=216.3$ *mm* and thickness $t=8$ *mm*. Both members are made of steel using modulus of elasticity *(E)* is 205×10^3 N/mm^2 and yield stress (σ_y) is *235* N/mm^2. The rigidities and strengths of the joints are separately calculated using nonlinear finite element technique, as fully described later in Chapter 3.

2.3. Boundary Condition and Distribution of Load

The roof is assumed to be initially subjected to a vertical dead load P_0, given at the upper and lower node of the strut members. Arches at the boundaries where all strut nodes have to be pin-supported (restrained in the x, y and z directions) at their upper and lower joints are exempted.

2.4. Geometrical Imperfections

Since effects of geometrical imperfections are large in case of single layer lattice roofs, the present study assumes a deformation distribution, $W_{imp}(x,z)$, for geometrical imperfections, based on the first buckling mode obtained by using FEM eigenvalue analysis for each model of lattice roof. Then normalization of deformation is done, so that the peak value of $W_1(x,z)$ is set as 1.0 for the maximum deflection.

$$W_{imp}(x,z)=w_{i0}\cdot W_1(x,z);\ w_{i0}=\pm\min(L_x,L_z/1000) \quad ..(1)$$

In this paper, the maximum amplitude of imperfection, w_{i0}, for the presented roof is assumed to be uniform, around *60 mm* in the negative y-direction. This value is resulted from Eq. (1) with L_x is equal to L_z about *60000 mm*.

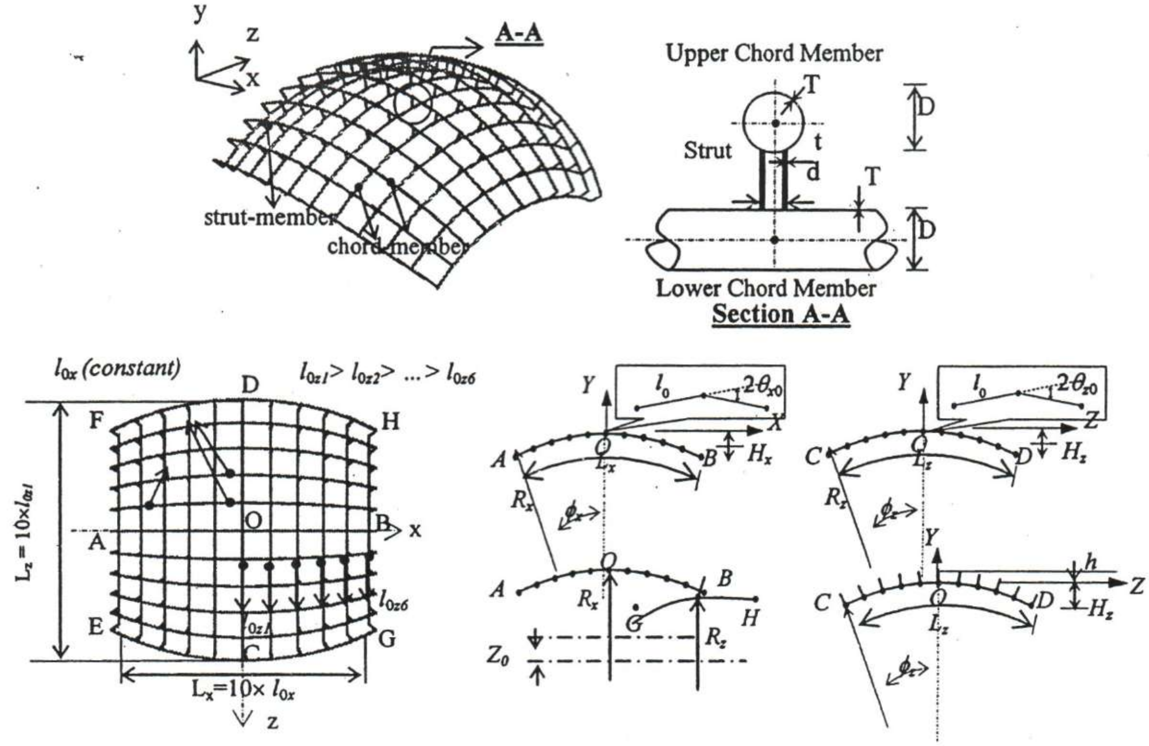


Figure.1(a) Two-Way Single Layer Lattice Roof with Nodal Eccentricity (upper)
(b) Configuration of Roof: Geometrical Model (lower-left) and Geometrical Parameters (lower-right)

3. NUMERICAL MODEL OF TUBULAR T-JOINTS

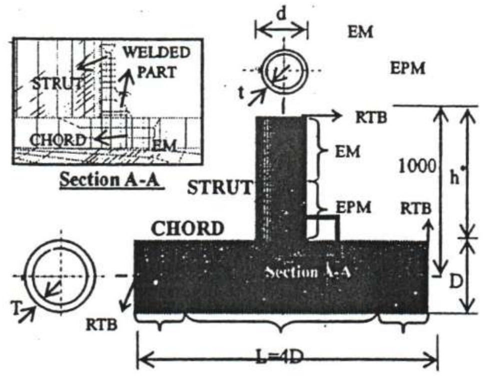
By following the procedure for modeling tubular joint developed by Cao et. al. (1997), the tubular T-joint model is successfully modeled, as seen in Fig.2. Both tubular members, brace and chord, are connected each other using welding part, which is modeled according to welding standard which is given by AIJ (Architectural Institute of Japan, 1993). However, in this paper, the welding part is not installed by a crack model. Therefore, any failures due to crack propagation which are usually occurred in the welding part of tubular joint are not considered.

3.1 Geometrical and Material Properties

The tubular members, with geometrical properties mentioned in subchapter 2.2 are made of steel using modulus of elasticity *(E)* is 205×10^3 N/mm^2 and yield stress (σ_y) is 235 N/mm^2. The stress-strain relationship is approached by bi-linear model with Von-Misses yield criterion, whereas plasticity condition is represented by associated flow rule and isotropic hardening rule with hardening parameter (H) of E/1000.

3.2 Rigidities and Strength of T-Joint

Rigidities and strengths of the tubular T-joint are determined by numerical calculation based on nonlinear FEM under three types of basic loading; in-plane bending *(IPB)*, out-of-plane bending *(OPB)* and axial loading *(AXL)*. Table 1 shows the results of calculation for all types of loading. However for axial loading case, the result is not shown in the table because of very small value of deformation given by this case.



Note:
D : Diameter of the chord (mm)
T : Thickness of the chord (mm)
L : Length of the chord (mm)
d : Diameter of the strut (mm)
t : Thickness of the strut (mm)
h* : Length of the strut (mm)
RTB : Rigid Thin Body
EM : Elastic Material
EPM : Elasto-Plastic Material

Figure.2 Numerical Model of T-Joint

Table1. Rigidities and Strength of T-Joints under IPB and OPB.

K_{IPB} (kN.m/10^{-3}rad)	K_{OPB} (kN.m/10^{-3}rad)	$M_{y,IPB}$ (kN.m)	$M_{u,IPB}$ (kN.m)	$M_{y,OPB}$ (kN.m)	$M_{u,OPB}$ (kN.m)
33.71	10.01	323.0	337.0	221.0	247.0

Later, the rigidities and strengths given by Table.1 are used in all T-joints of the roof structure which is geometrically shown in Chapter 2.

3.3 Validity of Numerical Results

To check the validity of the numerical calculation (denoted by full lines), Fig. 3 shows its comparison to experimental results (denoted by dotted lines) given by some previous works. Akiyama's experiments are used to validate the results of in-plane bending and out-of-plane bending cases, while Makino's work (Akiyama, 1988) is used to validate the axial loading case. In general, all results show a good agreement between two approaches.

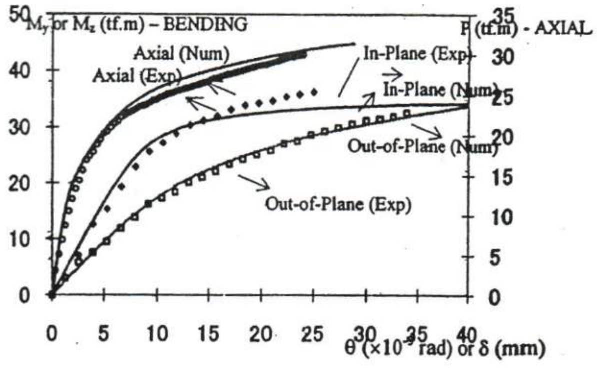


Figure.3 Validation of Nonlinear FEM of T-Joint with Experimental Results

4. DESIGN FEASIBILTY OF THE ROOF

Fig.4 shows the design feasibility the roof under elastic and elasto-plastic analysis. Based on the criteria specified in Design Standard for Steel Structures published by Architectural Institue of Japan 2002, the maximum displacement under the critical load from elastic analysis should be less than or equal to $\delta_{max}=L_Z/300=60000/300=200$ *mm.*

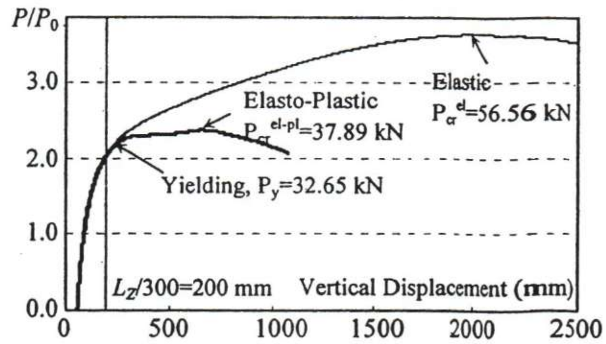


Figure.4 Static Response of Loading-Displacement

It means the load that gives $\delta_{max}=20$ *cm* can be notified as the critical load. This is found as $P_{cr}/P_0 = 2.06$ leading $P_{cr}=31.1$ *kN/node* or in term of load intensity, $p_{cr,design}=2\times 31.1$ *kN/(6x6* $m^2)=1.73$ *kN/m²*.

According to its geometry, this roof practically can be used to support the dead load around *0.86 kN/m²* and additional vertical load like a snow load up to *0.87 kN/m²*. This value is corresponding to regions under moderate snow loads in Japan.

5. CHARACTERISTIC OF T-JOINT UNDER A STATIC REPEATED LOADING

The repeated uniform snow loads (1 kN/m^2 per each layer of roof) are represented by giving five low cycles (loading-unloading steps) to the present roofs. The first cycle is given until the deformation up to δ_1=10cm, the second cycle is up to δ_2=20cm, followed by the third cycle is up to δ_3=30cm, then the fourth cycle is up to δ_4=40cm and the last is up to δ_5=50cm. All unloading steps are given until P=0 kN. Two reference points are taken; first is at the critical joint (Fig.5a) and second is at the maximum vertical deflection point (Fig.5b).

The remarkable feature found after this study is its self recovery system for displacements since large displacements occurred due to heavy snow loads almost vanish after unloading [3], even until δ_5=50cm, the residual plastic deformation at the critical joint is smaller than 10cm. The reason of this recovery is the fact that most of the deformations attribute to elastic strains in the structures (see Fig.3a). And once an overload is given, some parts at the ends of strut members are deformed plastically without any damage to main arches.

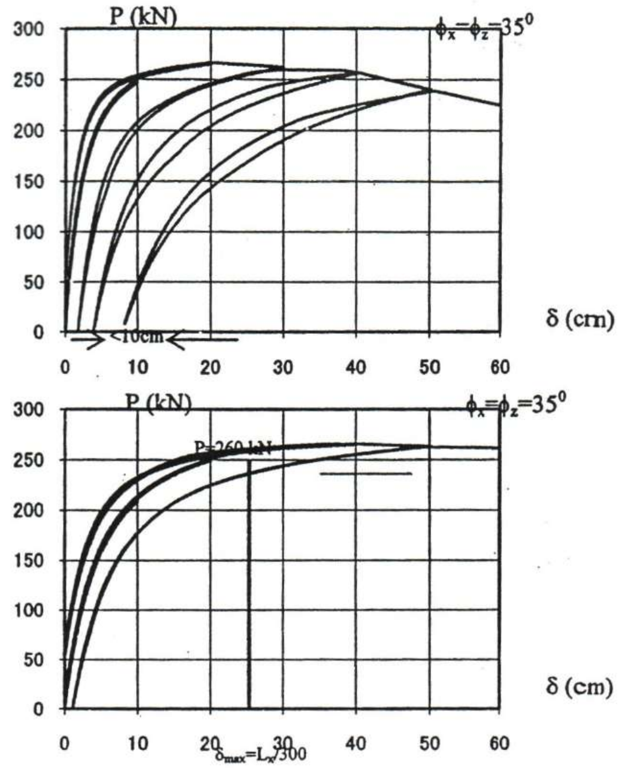


Figure.5 Static Responses of Roof Structure under Repeated Loading: (a) at the critical joint (top) (b) at the maximum vertical deflection joint (below)

6. CHARACTERISTIC OF T-JOINT UNDER A DYNAMIC LOADING

In term of dynamic loads such as earthquake motions, the plasticization of joint system can be considered is able to absorb energy due to the strong disturbances. The description below is used to justify this prediction under earthquake motion.

6.1 Earthquake Motion

El-CentroNS(1940) with 50 seconds duration and peak acceleration in range of 100cm/s^2 to 1250cm/s^2 are adopted for the horizontal seismic ground motion as presented in Fig. 4.

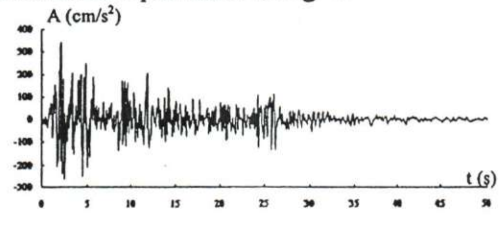


Figure. 4 Time history of El-CentroNS

6.2 Description of Dynamic Calculation

Average acceleration method of Newmark-β scheme with β=1/4 is used for numerical integration with time interval for calculation Δt is 0.005 sec. The Rayleigh damping is assumed to the roof with 2% damping constant at periods of T_1=1.5 sec and T_2=0.1 sec.

6.3 Results in Term of Absorbed Energy

Energy absorbing capability is determined by examining the roof under earthquake loadings with maximum acceleration A_{max} is varied between *100* to *1250 cm/s²*. Several types of energy then are evaluated. The consumed energy is summation between kinematics, damping and strain energy, as shown in Fig.5. The kinematic energy is almost zero after the earthquake.

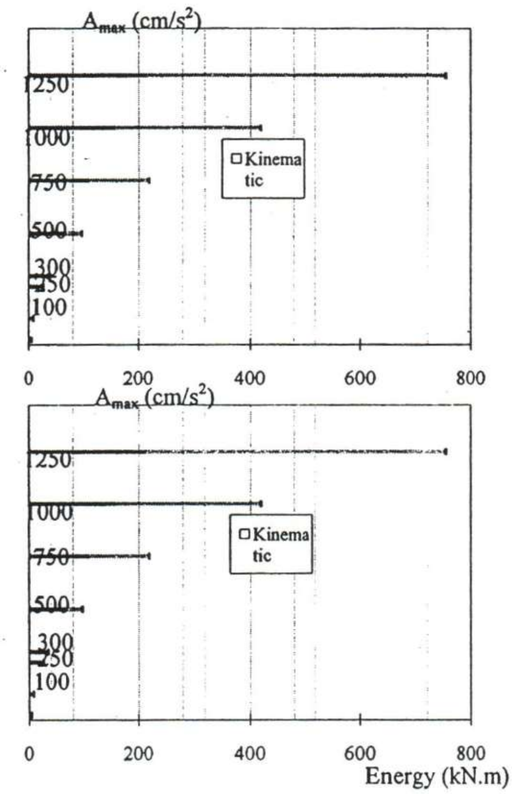


Figure.5 Absorbed Energy: (a) when earthquake is loading in x-direction, and (b) when earthquake is loading in z-direction

Table 2. Percentage of strain energy when earthquake is loading in x-direction (left).

A_{max} (cm/s²)	% Strain Energy (Loading in X-Direction)	
	Arch	Strut
100	89.0	11.0
250	89.0	11.0
300	85.6	14.4
500	14.6	85.4
750	3.7	96.3
1000	1.5	98.5
1250	0.8	99.2

Table 3. Percentage of strain energy when earthquake is loading in z-direction (right).

A_{max} (cm/s²)	% Strain Energy (Loading in Z-Direction)	
	Arch	Strut
100	89.0	11.0
250	89.0	11.0
300	84.4	15.6
500	10.9	89.1
750	2.1	97.9
1000	0.9	99.1
1250	0.5	99.5

Table 2 and 3 show the exact values and also the percentage of strain energy absorbed by the arches and struts during the earthquake given in the *x* and *z* directions respectively. As a general remark, it can be noticed that the struts have mainly absorbed the strain energy when the structure is subjected to the earthquake with maximum input acceleration $A_{max} \geq 500$ *cm/s²*, while for ground motion $A_{max} \leq 300$ *cm/s²*, most of the strain energy is absorbed by the arches. This phenomenon may be explained with regards to the structures performance at earthquake loading as follows. During a strong earthquake shaking, the plasticity will firstly occur at the strut joints by yielding. However the strain energy would be absorbed very well by the T-joints when yielding takes a place, reducing the possibility of some unexpected damages to the main arches. At the weak earthquake, strain energy is mainly absorbed by the main arches; but as the deformations are quite small in this case, the main arches would be in safe condition.

7. CONCLUSION

The present paper has investigated the the effect of the tubular T-joints on the overall characteristics of the roof system under loadings. The presumptions assumed in the study are that (1) the plan for the roofs is rectangular with a size of $L_x \times L_z$, where L_x and L_z are *60 m*, (2) the rise is relatively shallow with *30°* and *25°* for the half open angle respectively in the *x* and *z* directions, (3) the length of strut member placed between orthogonal arches is *250 cm*, (4) the boundaries of roof at all peripheries are pin supported, (5) the roof has geometrical imperfections of which peak amplitude is $\pm L_x/1000$, and (6) the dead load is uniformly distributed.

Several important conclusions can be drawn as follows.

1. The roof is feasible to be applied in construction of long span structures.
2. The benefit of using the T-joint struts against the repeated snow loads is that the residual plastic deformation (δ_0) due to heavy loading is small compared to the maximum displacement. The reason of this recovery is the fact that most of the deformations attribute to elastic strains in the structures, and once an overload is given, some parts at the ends of strut members are deformed plastically without any damage to main arches
3. The benefit of using the T-joint struts against earthquake is that the yielding of strut joints has a good capability to absorb some of seismic energy against severe earthquakes; therefore any plastic residual deformations that occurred after the dynamic loads are much smaller than maximum deformation during the earthquake. The results are very beneficial to reduce any heavy damages to the main arches. Moreover, it implies that the proposed roof has a kind of damage-control characteristic against severe earthquake motion.

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