편심이 고려된 강관-가셋트 접합부의 극한 내력

A Study on the Ultimate Strength of Tube-Gusset Connection Considering Eccentricity

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요 약 : 본 연구에서는 편심 축력을 받는 가셋트-강관 접합부의 극한 내력을 파악하기 위하여 실험 및 유한요소해석을 수행하였다. 가셋트-강관 접합부의 내력에 영향을 주는 요소는 강관의 직경, 가셋트판 길이, 축력과 횡력의 비, 횡력에 의한 편심 등으로 이들이 주재의 좌굴내력에 미치는 영향을 정량적으로 파악하여 접합부 강도식을 제안하였다. 특히 횡력에 의한 편심이 주재에 작용할 때 이를 설계식에 반영하기 위하여 횡력을 등가의 모멘트 및 편심 축력으로 대치한 수치 모형을 제시하였다. 결과적으로 접합부에 작용하는 외력을 주주재 축력, 모멘트, 편심 축력으로 분해하고 각 외력에 대한 독립적인 극한내력을 구한후 이들의 상관 관계식을 구함으로써 접합부 극한강도식을 제시하였다.

ABSTRACT : A numerical analysis and experimental study were performed to investigate the behavior and strength of tube-gusset connection subjected to axial and lateral forces. To investigate the behavior of the connections, experiment was conducted by applying three directional loads. Local buckling and local plastic bending deformation of the connection were observed from the test. Analytical results were compared with test results for the limited cases. Primary interests here are the effect of eccentricity on the strength of the connection. To suggest a formula for the strength of tube-gusset connection, lateral forces were replaced with equivalent wall moment and eccenrtric vertical component force of lateral force. Ultimate strength formula for the each force was proposed. Finally, nondimensionalized ultimate strength interaction relationships between the wall moment of tube(M_w), vertical axial force(P_v), and eccentric vertical component of lateral force(P_e) were formulated through parametric study.

Introduction

Tubular members, recently used as main post and bracing member in a high voltage (765kv) electric transmission tower in Korea, show good structural performance such as tosional rigidity, local and overall buckling strength. In the design of con-

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본 논문에 대한 토의를 2001년 10월 31일까지 학회로 보내주시면 토의 회답을 게재하겠습니다.

nection, tube-gusset plate type has been introduced for the purpose of efficiency of erection of tower in the field. Tube-gusset plate connection, comprising the main part of panel points of trusses, determines the safety and reliability by their resisting capability against failures such as plastic deformation, local buckling and fatigue crack. In order to establish the rational design for the connections, it is absolutely inevitable to accumulate exact information about the ultimate strength for various geometry and loading conditions. In current design[3),(4),(5),(6], however, strength formula for the tube-gusset plate joint is proposed only in the limited case because of its complexity of behavior. Many studies have been done to suggest a strength formula for tube-gusset type connections subjected to lateral and axial forces, which have no eccentricities. Kurobane carried out the test for the TP and XP joints subjected to lateral compressive and tensile forces.[(7)] Also Werdenier suggested a formula for the single and double gusset plate joints.[(8)] Combined effect of axial force and lateral force was not considered in the research. Only local strength for the moment induced by lateral forces were obtained. In an actual member, however, eccentricities can not be avoided and this causes an additional moment at the joint. The eccentricity may increase or decrease the strength of the joint in accordance with the location of the lateral force.[(1),(2)] It is necessary that tube-gusset connection problem should be dealt by considering the effect of eccentricity for more rational design method. This paper describes the behavior and strength of tube-gusset connection through experiments and analytical analysis (F.E.M) based on inelastic large deformation. The analytical results were compared with test results for verification. Especially eccentricity was considered by replacing the lateral forces with wall moment of tube(M_w) and eccentric vertical component force(P_e). Consequently, ultimate strength interaction relationships between the wall moment of tube(M_w), vertical axial force(P_v), and eccentric vertical component force of lateral force(P_e) was established. The validity for the replacement was reviewed in the practical range of geometry.

Current design practice

In electric transmission tubular tower, K type connections are generally used in main post member, and gusset-plate connections are used between main post and bracing member as shown in the Fig. 1. In addition to vertical force, lateral forces to tube-gusset plate are classified into axial forces (P), shear forces (Q) and bending moments (M). Each force is computed as

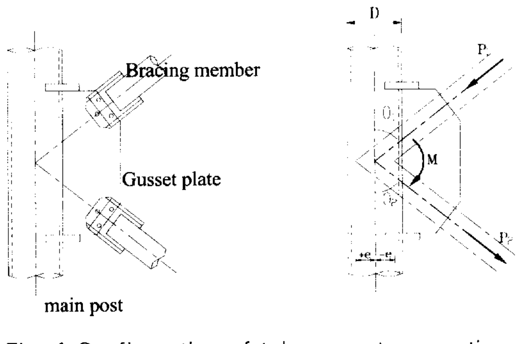


Fig. 1 Configuration of tube-gusset connection

$$M = (P_1 \cos\theta_1 + P_2 \cos\theta_2)D/2,$$
$$P = P_1 \sin\theta_1 + P_2 \sin\theta_2,$$
$$Q = P_1 \cos\theta_1 + P_2 \cos\theta_2$$

Since, hollow circular section is more susceptible to local deformation due to the forces, the details of the connection should be determined through rigorous analysis. Unfortunately, however, current design specifications[5] propose no specific formulas because of its complexity of behavior. Partially, in Japanese design guide for tubular structures(AIJ)[3] and journal of JSSC[4], approximate strength formula based on experiment has been proposed for a limited case, which considers only effect of moment on the wall. Consequently, the axial force that has significant effect on the strength of the connections was not reflected on the strength Equations.

Outline of experiments

Static test were conducted on 9 steel tube-gusset connections to investigate the effect of stress concentration and ultimate strength, and to compare the results of analytical model. In order to simulate the actual loading conditions on the connections, it was necessary to design a suitable loading frame for gusset joint as shown in Figure 2. Three independent loading unit was installed to vary the ratio of vertical load to lateral(compression and tension) loads. The specimens were free to rotate at the end. The diameter of tube was 76.6mm which is about one-third of the tube of 765kv electric transmission tower constructed in KOREA. The material used is SS400 specified in KS(σ_y=2.4t/cm^2). The test specimens are classified into their geometrical configuration as shown in Table 1. To prevent a failure of gusset plate, thickness of gusset plate was fixed to 8mm. For the measurement, 9 pieces of single-axis type strain gage are attached to the area where the higher stresses are likely to occur. 4 linear Main concern of the experiment is to observe the failure pattern at the ultimate state when the influential parameters are varied. The following parameters are considered to be important: (1) Length of gusset plate (B), (2) Ratio of vertical load to lateral load (P_l/P_v), P_l(lateral force) = P_1(compression) = P_2(tension), (3) eccentricity of lateral force (e). Experiment was carried out in the limited case because of experimental limitation.

displacement transducer were positioned axisymmetrically about the center of tube.

Table 1. Dimensions and Material Properties of Test Specimens

Specimens	D(cm)	T(cm)	B(cm)	L(cm)	λ	σ_y(t/cm^2)
TA00	7.66	0.15	20	40.0	15.06	3.261
PA00	7.66	0.15	20	40.0	15.06	3.161
PA10	7.66	0.15	20	40.0	15.06	3.268
PA30	7.66	0.15	20	40.0	15.06	3.256
PA70	7.66	0.15	20	40.0	15.06	3.172
PA31	7.66	0.15	20	40.0	15.06	3.056
PA71	7.66	0.15	20	40.0	15.06	3.297
PB30	7.66	0.15	16	40.0	15.06	3.211
PC30	7.66	0.15	12	40.0	15.06	3.155

TA00 — eccentricity of lateral force
(0:e=0, 1:e=D/2)
— lateral force ratio=P_l/P_v
(0%, 10%, 30%, 70%)
— gusset plate length
(A=20cm, B=16cm, C=12cm)
— gusset plate (T:×, P:O)

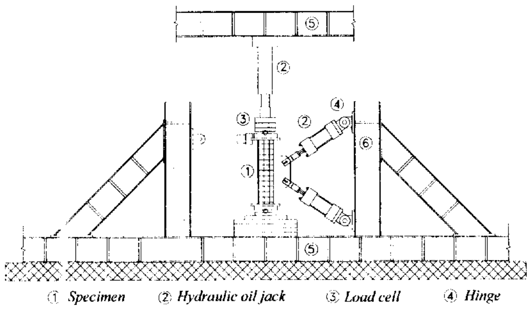


Fig. 2 Test setup for vertical and lateral load

Test results

Effect of lateral load - To investigate the influence of lateral loads, lateral load was applied with a ratio of 10%, 30%, 70% to vertical load and each specimen was designated as PA10, PA30, PA70. The vertical component of lateral load is distributed uniformly along the section of tube and horizontal component of lateral load is zero with respect to center of tube. But, in the respect of the attached line of gusset plate, horizontal component of lateral load produces bending moment. Therefore, ultimate capacity of the connection is determined by local buckling due to vertical compressive force or local plastic deformation due to horizontal force. It was observed that ultimate capacity was governed by local buckling in case of PA10. Ultimate axial load was $0.989P_y$. In case of PA30, local deformation due to bending was noticeable in the ultimate state, and finally the specimen was failed by horizontal component of lateral load. Just after the ultimate state, local buckling occurred at the top of the specimens. When the lateral load was highly increased to 70%(PA70), bending deformation of the wall was remarkably developed at the initial stage of loading response and local buckling was not occurred in the whole ranges.

Effect of eccentricity - The effect of eccentricity was investigated for the case of 30% and 70% of lateral force ratio. PA30 and PA70 have no eccentricities with respect to center of tubular section. PA31 and PA71 have eccentricities of $D/2$ and the eccentricities coincide with the attached line of gusset plate. From the experimental observation, it was observed that the specimens without eccentricity were failed by local plastic bending deformation, and the specimens with eccentricity were failed by local buckling. However, as lateral force ratio is decreased, failure of the joint was governed by local buckling regardless of eccentricity. It is interesting that ultimate strength of the specimens with eccentricity was higher than that of the specimen without eccentricity. As lateral force ratio increased (P_l/P_v=0.7), ultimate strength of the specimen with eccentricity was increased about 15% as shown in the Table 5 (see PA70 & PA71).

Effect of length of gusset plate - Length of gusset plate is an important factor in determining the ultimate strength of tube-gusset connections because lateral force is transformed to wall moment of tube through the gusset plate. As the gusset length increases, the coupled lateral forces due to wall moment is reduced. The effect of length of gusset plate was studied for three cases; B/D ratio = 2.6, 2.1 and 1.6, in order to cover the range most frequently used in common practice. Ultimate capacity of three specimens are governed by local plastic deformation since the effect of lateral load was quite high as P_l/P_y =0.3. Local plastic deformation rather than local buckling was observed even in the case of low lateral load. The ultimate strength of PC30 was reduced to 77% of PA30 (PA30=10.2t, PC30 =7.88t). Since ultimate capacity depends on the interaction between axial force and bending moment, usually failure occurs in the form of local buckling, local plastic bending deformation or combined local buckling and bending deformation. Figure 3 shows typical examples of local buckling and plastic bending deformation, which was observed in the test.

Finite Element Analysis

Analytical studies were performed by using finite element method. To obtain the ultimate strength, finite element analysis using ABAQUS was performed in the inelastic range. Residual stress was not considered in finite element model, since the residual stress

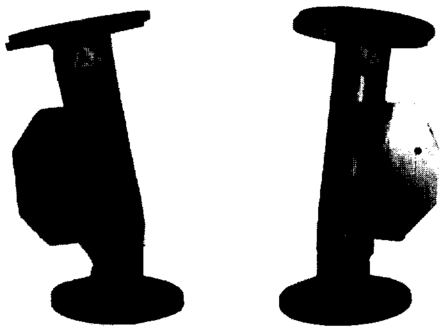


Fig. 3 Typical Failure Mode of Tube-Gusset Connections

was found out to be insignificant from the stub column test. Stress distribution and concentration was examined in the elastic state as well as inelastic state. The result was compared with the experimental results for verification. Finite element discretization was carried out by using 4-node shell element. The ultimate strength obtained from the finite element analysis was compared with experimental results. Table 2 shows good correspondence of 4% deviation between the test results and analytical results.

Two diagonal tensile/compressive lateral loads were replaced by M_w and P_e in order to facilitate a parametric study to propose a strength formula of the connections as shown in Fig. 4. To verify the validity of the replacement of loads, lateral forces and eccentricities were varied and compared with

Table 2. Comparisons of Tests with Analytical Results

Specimens	P_y(t)	P_u(t)	P_u/P_y	P_{ua}/P_{ya}	P_{ua}/P_u
TA00	11.54	11.41	0.989	0.9723	0.954
PA00	11.19	11.00	0.983	0.9714	0.988
PA10	11.57	10.26 (11.28)	0.887 (0.975)	0.8803 (0.9678)	0.96
PA30	11.526	7.851 (10.20)	0.681 (0.885)	0.7078 (0.9196)	1.009
PA70	11.23	5.458 (9.28)	0.486 (0.826)	0.4692 (0.7971)	0.962
PA31	10.82	7.394 (9.61)	0.683 (0.888)	0.7203 (0.9357)	1.09
PA71	11.67	6.207 (10.52)	0.532 (0.901)	0.5335 (0.9071)	0.962
PB30	11.367	7.420 (9.64)	0.653 (0.848)	0.6586 (0.8562)	0.992
PC30	11.17	6.066 (7.88)	0.543 (0.705)	0.5442 (0.7078)	1.004

P_y : Yield strength(test result)
P_u : Ultimate strength(test result)
P_{ya} : Yield strength(analytical result)
P_{ua} : Ultimate strength(analytical result)
( ) : Axial + Vertical component force

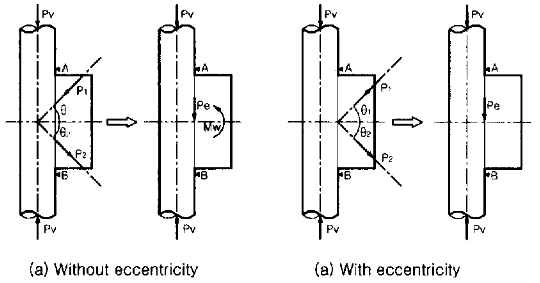


Fig. 4 Replacement of Lateral Forces

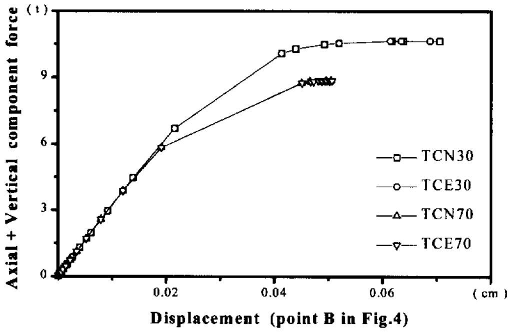


Fig. 5 Comparisons between original and replaced model(without eccentricities)

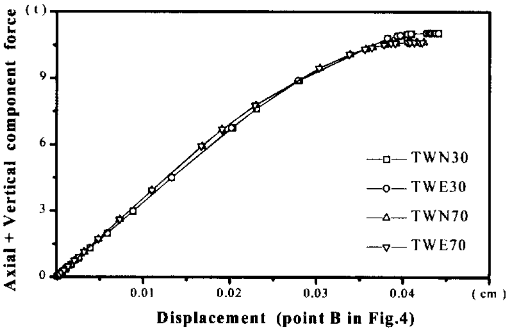


Fig. 6 Comparisons between original and replaced model(with eccentricities)

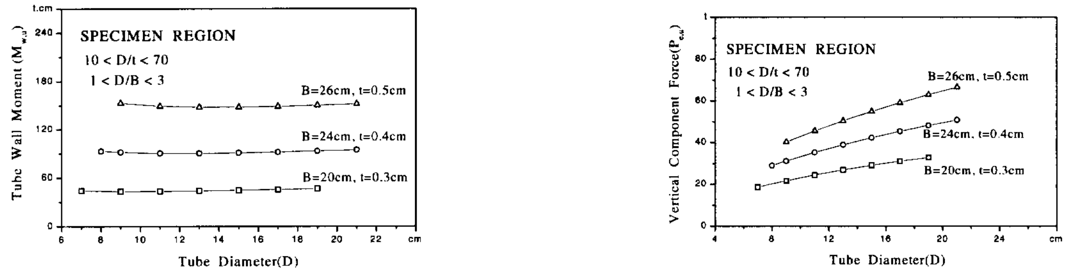
original models. Lateral force ratio was varied from 30% to 70%. Same ultimate strength was obtained for each case as shown in the Fig. 5 and Fig. 6. The replaced model showed good coincidence with 1% deviation for the original models. The original model and replaced model is classified as follows.

TCE00 - lateral force ratio(30%, 70%)
- replacement of lateral force (N: original model, E: replaced model)
- eccentricity (C: without eccentricities, W: with eccentricities)
- section type(T: circular tube)

To examine the local effect excluding overall bending and buckling, slenderness ratio of tubular model was fixed lower than 20. The vertical loads (P_v and P_e) and the moment (M_w) were applied simultaneously to simulate the actual loading condition in the transmission tower. Since the three forces were uncoupled, displacement control scheme to obtain the descending branch of load-deformation curve was not available in Fig. 5 and Fig. 6. Only ascending branch and ultimate strength was obtained. To propose ultimate strength equations, the basic joint parameters such as tube diameter (D), wall thickness ratio (t), gusset length (B) was selected.

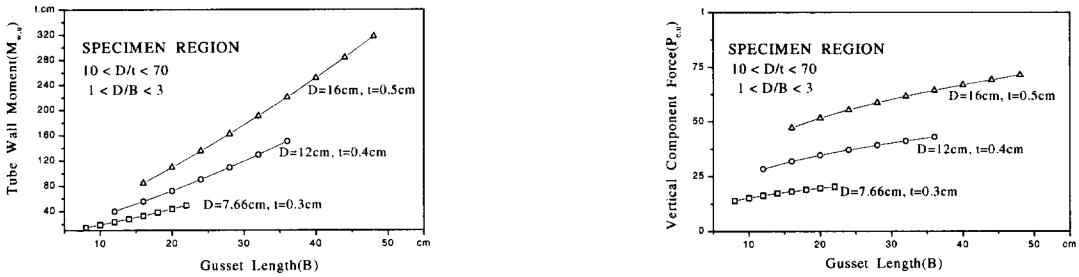
Parametric Study

To suggest the ultimate strength for M_w and P_e in terms of B, D and t, parametric study was carried out by finite element analysis. The effect of each parameter on the ultimate strength was investigated for various geometries. Here the eccentricity (e) is not involved, because effect of eccentricity is already reflected on the replaced model. Influence of the parameters on the $M_{w.u}$ and $P_{e.u}$ is presented in the Fig. 7,8 and Fig. 9. Fig. 7-a shows that diameter of the tube does not have much effect on the $M_{w,u}$. On the other hand, thickness and gusset length have a significant effect on the $M_{w,u}$. Fig. 8-a and Fig. 9-a show linear and quadratic relationship between the parameters and the strength. Similarly, effect of the parameters on the $P_{e,u}$ was investigated. Diameter and thickness affect on the strength linearly, and gusset length does not have much effect on the strength as shown in Fig. 7-b, 8-b and 9-b. Usually local buckling is likely to occur by axial force and D/t is a main parameter affecting



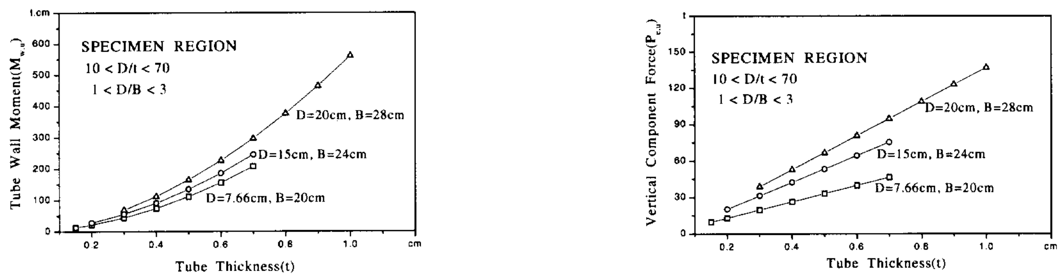
(a) (b)

Fig. 7 Influence of Diameter on the Ultimate Strength $M_{w,u}$ & $P_{e,u}$



(a) (b)

Fig. 8 Influence of Gusset Length on the Ultimate Strength $M_{w,u}$ & $P_{e,u}$



(a) (b)

Fig. 9 Influence of Thickness on the Ultimate Strength $M_{w,u}$ & $P_{e,u}$

the buckling strength. However, value of D/t is usually fixed less than the value 70 in actual tube-gusset connections, elastic local buckling is hard to occur. In this case, local buckling due to stress concentration by the P_e occurs, and the buckling is not directly related to D/t. Finally, ultimate strength for the M_w and P_e was obtained through a regression analysis and derived formula is as follows. The parametric study was performed in the range of $10<D/t<70$, $1<D/B<3$ in order to cover the actual geometry in practice.

$$P_{v,u}=P_y$$
$$M_{w,u}=\{0.34(D/t)^{0.6}+0.8(B/D)+2.9\}Bt^2\sigma_y$$
$$P_{e,u}=1.05((B/D)^{0.5}-0.22/(B/D)^{-1}-0.0025(D/t)+1)Dt\sigma_y$$

Comparisons with Current Design Guide

Proposed strength formula was compared with Japanese and Canadian design guide [(3),(4),(6)] and the comparisons are summarized in Table 3. Here, the ultimate strength for vertical component force($P_{e,u}$) was newly proposed. Also the results are compared with the results of rigorous finite element analysis. The proposed equations give more reliable results when it compared with a value of Japanese design guide (AIJ, and JSSC) for tubular connections as shown in the Figure 10, since the results of design guide was based on the experiments in the limited specimens.

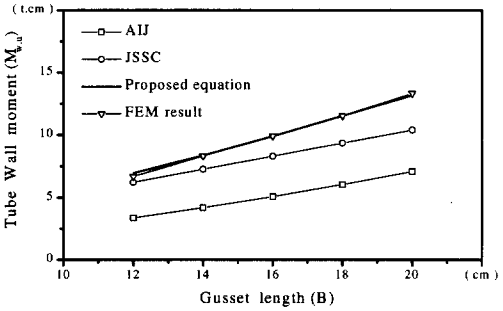


Fig. 10 Comparisons with current design guide

Ultimate Strength Interaction Equations

In actual tube-gusset connections, three forces M_w, P_v, and P_e works simultaneously, and 3 dimensional interaction relationship can be constituted. But, here, two dimensional relationship; M_w vs. P_v, P_e vs. P_v and M_w vs. P_e was formulated in advance.

M_w vs. P_v Interaction – The parameters B, D and t were varied to confirm the validity of nondimensionalizations of $P_v/P_{v,u}$

Table 3. Ultimate Strength Equations for Tube-Gusset Connections

	$M_{w,u}$	$P_{e,u}$
Proposed	$M_{w,u}=\{0.34(D/t)^{0.6}+0.8(B/D)+2.9\}Bt^2\sigma_y$	$P_{e,u}=1.05((B/D)^{0.5}-0.22/(B/D)^{-1}-0.0025(D/t)+1)Dt\sigma_y$
JSSC	$M_{w,u}=7Bt^2\sigma_y$	Not available
AIJ	$M_{w,u}=1.26B(\gamma^{0.2}+(B/2D)\gamma^{0.1})t^2\sigma_y$	Not available
CISC	$M_{w,u}=5\sigma_y^2(1+0.25\eta)f(n')$	Not available

Where, $\gamma=D/2t$, $\eta=B/D$, $f(n')=1$ for tension, $f(n')=1+0.3n'-0.3n'^2$ for compression.

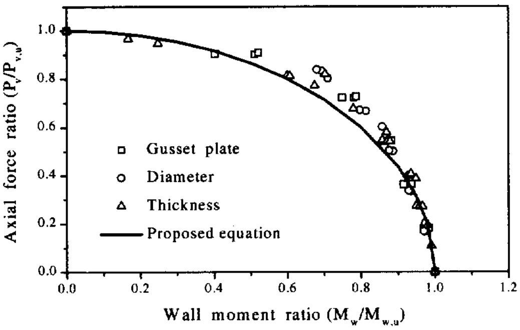


Fig. 11 P_v vs. M_W Interaction

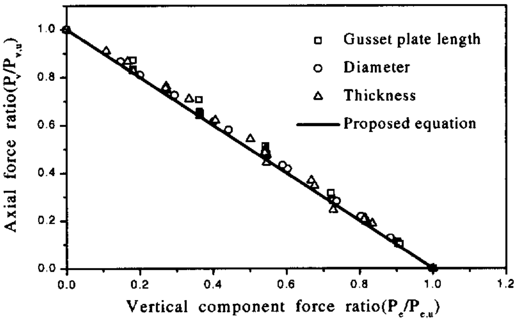


Fig. 12 P_v vs. P_e Interaction

and $M_w/M_{w,u}$. Here, $P_{v,u}$ is yield strength of tube($=P_y$), and $M_{w,u}$ is an ultimate moment capacity in the absence of vertical axial load P_v. The Fig. 11 shows that the conservative interaction curves can be obtained for each different value of parameters. Finally regression analysis based on the interaction curves was performed and following interaction relationship was obtained.

$$(P_v/P_{v,u})^2 + (M_w/M_{w,u})^2 = 1$$

P_v vs. P_e Interaction - Interaction curves between P_v and P_e shows quite linear relationship for all different values of parameters. It is deduced that effect of the moment caused by eccentric force on the tube was insignificant. Since local yielding or buckling due to two compressive forces (P_v and P_e) occurs before plastic bending deformation due to the moment. Since P_e works like P_v, ,the sum of two forces are constant and this gives linear interaction curves. Ultimate strength interaction curves are shown in the Fig. 12 and the following relationship was obtained.

$$(P_v/P_y) + (P_e/P_{e,u}) = 1$$

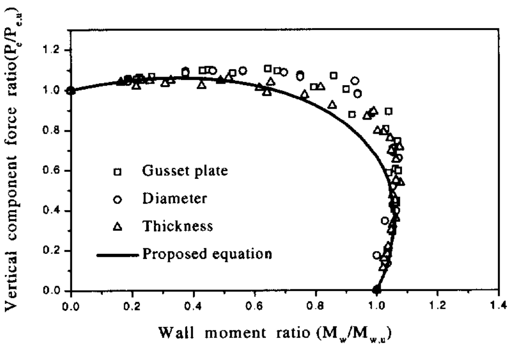


Fig. 13 M_w vs. P_e Interaction

M_w vs. P_e Interaction - *M_w and P_e* are applied with opposite direction as shown in the Figure 4. Since the two forces offset each other, a point exceeding a value 1.0 exists on the interaction curves as shown in the Fig. 13. The data points are somewhat scattered when it compared with the above two relationship. Therefore, interaction equation was determined quite conservatively and derived formula is as follows.

$$3(P_e/P_{e,u})-2(P_e/P_{e,u})(M_w/M_{w,u})+3(M_w/M_{w,u}) = 3$$

Summary and Conclusion

The present research was intended to

propose an ultimate strength of tube-gusset connections subjected to axial and lateral loads. Failure pattern for a various loading conditions was investigated from the 1/3 scale test. Analytical results verified through the test enable us to proceed numerical study to propose ultimate strength. Efficient replaced numerical model was suggested to consider the combined effect of axial force and moment. Ultimate strength for each component force such as $P_{v,u}$, $P_{e,u}$, $M_{w,u}$ was derived in terms of geometric parameters obtained from the regression analysis based on parametric study. Finally ultimate strength interaction relationship between each forces were formulated. Especially effect of eccentricity was efficiently introduced to the relationship. Three dimensional interaction relationships between P_v , P_e , and M_w will be developed in the next research.

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Notation

P_y : Yield strength(experimental result)
P_u : Ultimate strength(experimental result)
P_{ya} : Yield strength(analytical result)
P_{ua} : Ultimate strength(analytical result)
$M_{w,u}$: Ultimate strength for wall moment
M_w : Tube wall moment
$P_{v,u}$: Ultimate strength for vertical axial force
P_v : Vertical axial force
$P_{e,u}$: Ultimate strength for eccentric vertical component force
P_e : Eccentric Vertical component force of lateral force
P_l : Lateral force (= P_1 (compression) = P_2 (tension))
B : Gusset length
D : Tube diameter
t : Tube thickness
σ_y : Yield stress
λ : Slenderness ratio

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