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Ultimate strength of long-span buildings with P.E.B (Pre-Engineered Building) system

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Abstract. With the improvement of the quality of construction materials and the development of construction technologies, large-scale long-span steel frame buildings have been built recently. The P.E.B system using tapered members is being employed as an economically-efficient long-span structure owing to its advantage of being able to distribute stress appropriately depending on the size of sectional areas of members. However, in December 2005 and in February 2014, P.E.B buildings collapsed due to sudden loads such as snow loads and wind gusts. In this study, the design and construction of the P.E.B system in Korea were analyzed and its structural safety was evaluated using the finite element analysis program to suggest how to improve the P.E.B system in order to promote the efficient and rational application of the system.

Keywords: P.E.B. (Pre-Engineered Metal Building) system; tapered deep beam; lateral-torsional buckling; local buckling; ductile design

1. Introduction

Owing to the recent improvement in the quality of construction materials and the development of construction technologies, a large number of massive long-span steel structures have been built. The gabled Rahmen has been replacing the truss system in slanted roof frames due to the increase in labor costs. In the previously employed constant sectional area system where rolled H-shaped steel is used, the size of the member's section is determined based on that with ultimate stress because stress varies greatly in different locations. Therefore, material over-use or waste is very common. On the other hand, tapered members are mainly used in the P.E.B system where the design of members in accordance with design stress precedes the production of the members of various sizes. Thus, stress is distributed appropriately depending on the sectional sizes of members and the economic efficiency of long-span steel frame buildings is improved. The P.E.B system, which has been employed in military hangars or warehouses in the U.S. and U.K. to set up solid steel structures without delay, is now widely applied to industrial structures in the civilian sector in

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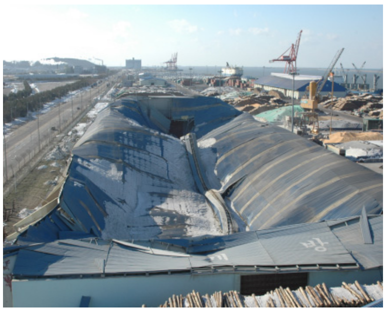
many developed countries(Hwang *et al*. 1991, Masika and Dunai 1995, Li *et al*. 2003, Li and Li 2004, Hernandez *et al*. 2005, Saffari *et al*. 2008, Seek and Murray 2008, Hong and Uang 2012, Abidelah *et al*. 2012, Lim *et al*. 2012, Dessouki *et al*. 2013). Owing to the benefits associated with the P.E.B system such as economy in material and labor costs, light weight, reduction in construction period and convenience in construction, it is expected that the system will be more widely employed. However, in December 2005, one (Building A) of the two P.E.B warehouse buildings in K City built in 2003 was completely destroyed and the other (Building B)



(a) Collapse of roof

(b) Snowfall of roof

(c) Deformation of rafter

Fig. 1 Building A in K City

(a) Snowfall of roof

(b) Lateral torsional buckling

(c) Web of rafter

Fig. 2 Building B in K City

(a) Collapse of roof

(b) Snawfall of roof

(C) Deformation of rafter

Fig. 3 Gymnasium of G City

was seriously damaged by heavy snow load and a sudden gust of wind. Also, in February 2014, gymnasium of M Resort in G City was collapsed and 10 people was died and more than 100 people was injured. Although the buildings were destroyed and damaged by a snow load three times stronger than the permissible snow load, the failure mode was brittle fracture caused by the local buckling at the web under compressive force and lateral torsional buckling at the flange below the rafter as shown in Figs. 1 to 3.

2. Design and construction of P.E.B system

The design, structural calculation and production for the P.E.B system are carried out by an automated design program developed exclusively for the system.

2.1 Design

The design process and steps for P.E.B system using the program are: (1) Inputting building width and length, span bay interval and column height and slope; (2) Inputting load; (3) Setting up load combinations; (4) Assigning flange width and web height for building design; (5) Automatically calculating web and flange thicknesses after 3-dimensional structural analysis; (6) Automatically printing structural calculation for confirmed sizes and proposal drawing (Andrade *et al*. 2007, Larue *et al*. 2007, MBMA 2002, Bazeos and Karabalis 2006, Polyzois and Raftoyiannis 1998, Yau 2006). Flange width and thickness calculated by the program range between 150-400 mm and 6-40 mm, respectively. Web width and thickness range between 200-3,500 mm and 6-20 mm, respectively.

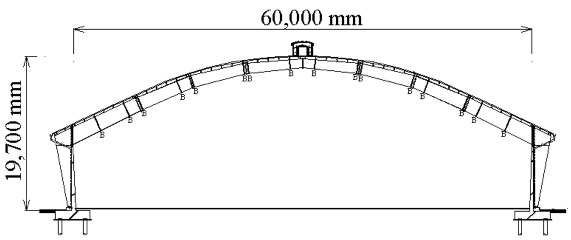
2.2 Current status

The P.E.B system can be used in various facilities such as commercial (warehouses, exhibition spaces and offices), agricultural (granaries and breeding farms), military (hangars, arsenals and barracks), production (factories and cold warehouses), public (schools and hospitals) and sports (gymnasiums and swimming pools). In the nonresidential building market (over than 25 m span) of Korea, with a steel quantity of 300,000 to 400,000 tons per year, the application of the P.E.B system is 70,000 to 100,000 (about 30%) tons which is 3,300,000 m^3 in land area.

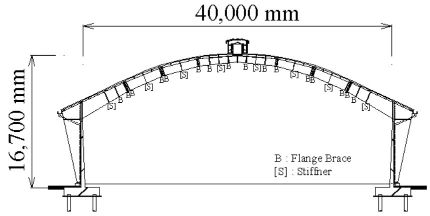
2.3 Considerations in design and construction

The end-plate connection featuring ease of field setup is commonly used in the P.E.B system because reducing the construction period is one of the critical issues in a system using tapered members. Except for in the P.E.B system, the end-plate connection is seldom used in Korea. The factors to be taken into consideration in the design and construction of the P.E.B system are as follows.

(1) Sudden load: In the P.E.B system, a lateral brace or flange brace may undergo brittle fracture upon a sudden load such as a storm or a gust of wind because of the large spans and large side walls in the system. In the design for wind load, the ASCE 7-95(1995) is used, which differs from Korean standards in terms of application method.
(2) Buckling: P.E.B buildings may experience local buckling and lateral torsional buckling under a flexural load stronger than a design load and may lose load capacity significantly



(a) B uilding A



(b) Building B

Fig. 4 Objects of structural safety evaluation

because deep rafters are used.

(3) Quality management: Unlike H-shaped steel, the P.E.B system can accommodate various sectional shapes. However, quality management throughout the whole process from production to construction is of critical importance to assure the required structural performance.

(4) Painting on joints: In Korea, painting on joints is not allowed because a joint with high-tension bolts is considered as a friction connection. In the U.S., painting on joints is allowed if the joints are bearing-type tension connections.

(5) Bolting: In Korea, KS1010 F10T bolts are used in the same way that generic high-tension bolts are used. In the U.S., snug tight bolted joints with ASTM A 325 bolts are allowed.

(6) Initial deformation at web: In the P.E.B system, web members undergo initial deformation because of flange-web welding. The U.S. has established regulations dealing with the initial deformation at the web. In Korea, however, no regulations have been established and sufficient studies on initial deformation at the web have not been made.

3. Evaluation of structural safety

3.1 Objects

The objects of the evaluation were two warehouse buildings in K City whose upper frames were made of SM490. Concrete was not included in the analysis. 16 flange braces were set up in the spots of possible local buckling and lateral torsional buckling in Building A. 16 flange braces and 8 stiffeners were set up in the spots in Building B.

3.2 Analysis model

As shown in Fig. 5, the Shell 181 element with 4 nodes each of which had 6 degrees of freedom

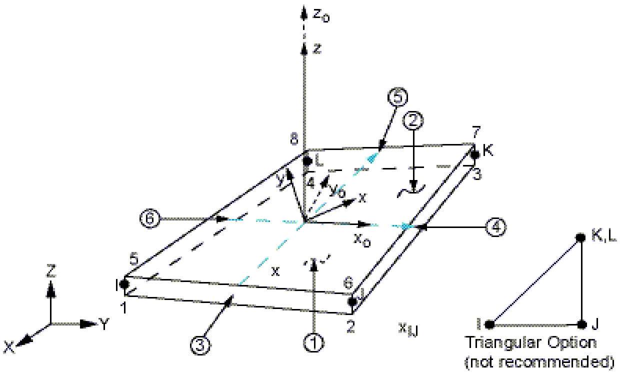
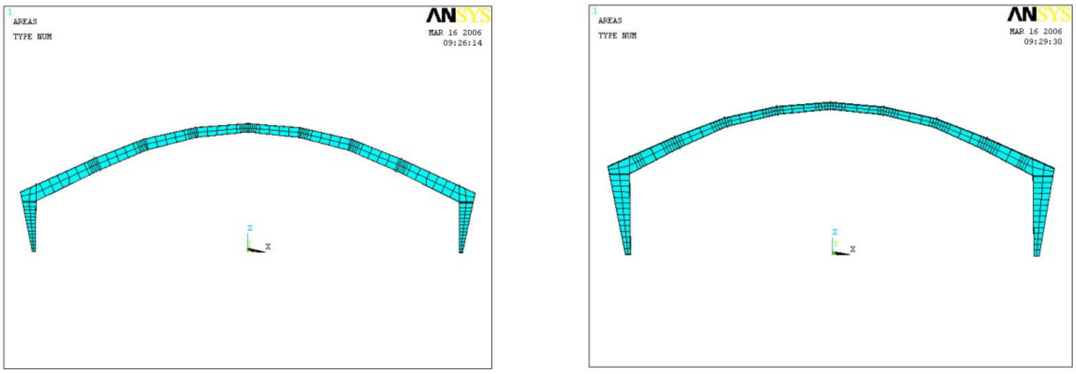
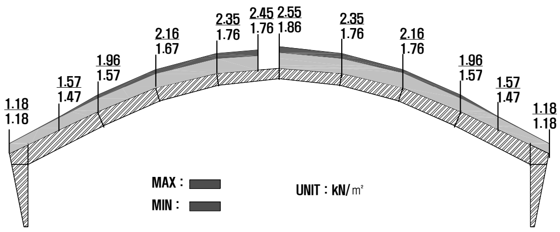


Fig. 5 Analysis element

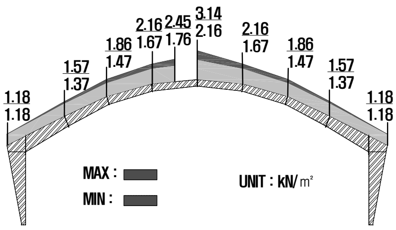


(a) Building A (b) Building B

Fig. 6 Analysis model



(a) Building A



(b) Building B

Fig. 7 Snow load

freedom (X, Y and Z axis-deformation and rotation) to support local buckling and lateral torsional buckling was used in the analysis. Fig. 6 shows completed model.

3.3 Loading conditions

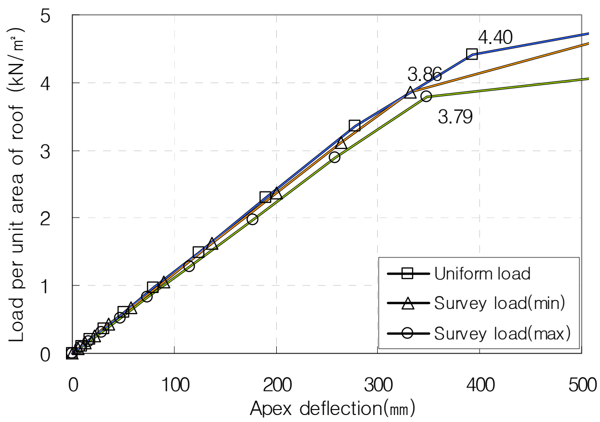
Loads to the roofs were converted to point loads to purlins and applied to the nodes. The maximum and minimum snowfalls were assumed as shown in Fig. 7 based on snow density (3.90 kN/m^3) measured at field investigation on December 22, 2005.

3.4 Results

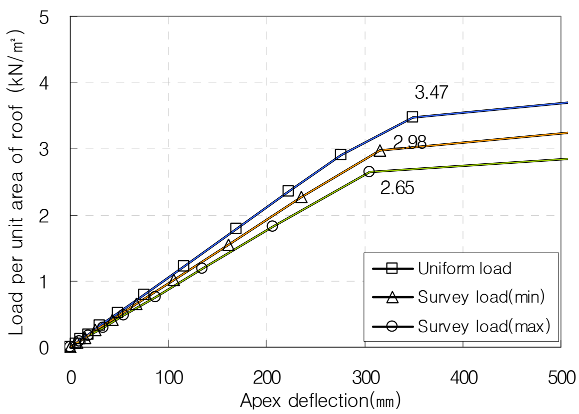
Design load for Building A and B were 1.30 kN/m^2 and 1.22 kN/m^2, respectively. The results of elastic and inelastic analyses for self weight + D.L + L.L and self weight + D.L + S.L were as follows.

3.4.1 Non-linear analysis

During the non-linear analysis, snow load per unit area of the roofs was increased at a constant



(a) Building A



(b) Building B

Fig. 8 Results of non-linear analysis

rate. Fig. 8 shows the relationship between load per unit are and Apex deflection compared between survey loads and uniform load. Building A yielded under the uniform load of 4.4 kN/m^2. However, while stiffness under survey loads was similar to that under uniform load, it yielded under the load of 3.79-3.86 kN/m^2. Building B yielded under the uniform load of 3.47 kN/m^2 and under the survey loads of 2.65-2.98 kN/m^2.

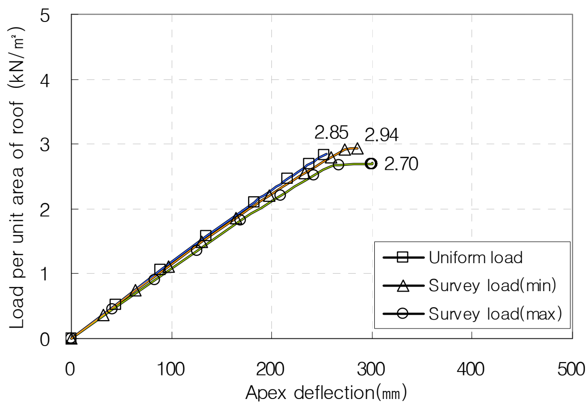
3.4.2 Buckling analysis

(1) Web-local buckling

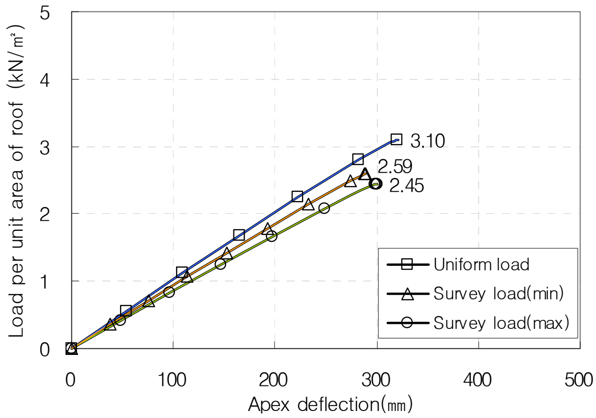
Table 1 shows the load per unit area upon web local buckling obtained from the analysis using

Table 1 Load per unit area upon web local buckling (Unit: kN/m^2)

	Uniform load		Survey load			
	Building A	Building B	Building A		Building B	
			max	min	max	Min
Load per unit area	1.01	2.01	0.13	0.94	1.59	1.65



(a) Building A



(b) Building B

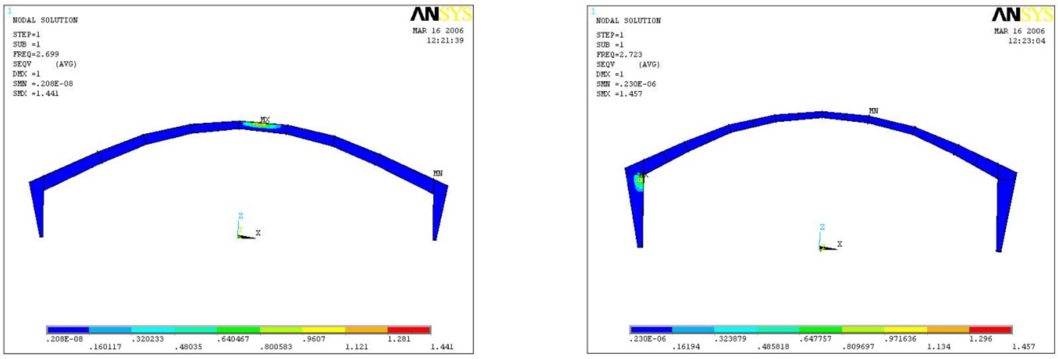
Fig. 9 Results of lateral torsional buckling analysis

Table 2 Load per unit area upon lateral torsional buckling (Unit: kN/m^2)

	Uniform load		Survey load			
	Building A	Building B	Building A		Building B	
			max	min	max	Min
Load per unit area	2.85	3.10	2.70	2.94	2.45	2.59

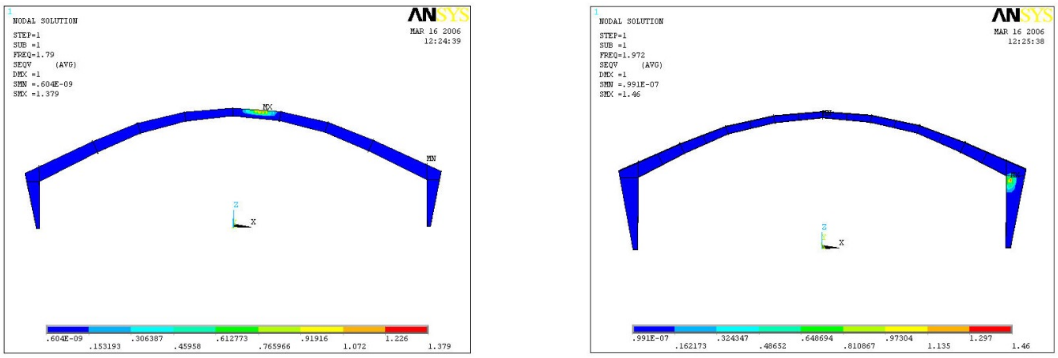
Table 3 Load per unit area upon flange local buckling (Unit: kN/m^2)

	Uniform load		Survey load			
	Building A	Building B	Building A		Building B	
			max	min	max	min
Load per unit area	2.85	3.46	0.33	2.67	2.69	2.81



(a) Building A (b) Building B

Fig. 10 Local buckling under uniform load



(a) Building A (b) Building B

Fig. 11 Local buckling under survey loads

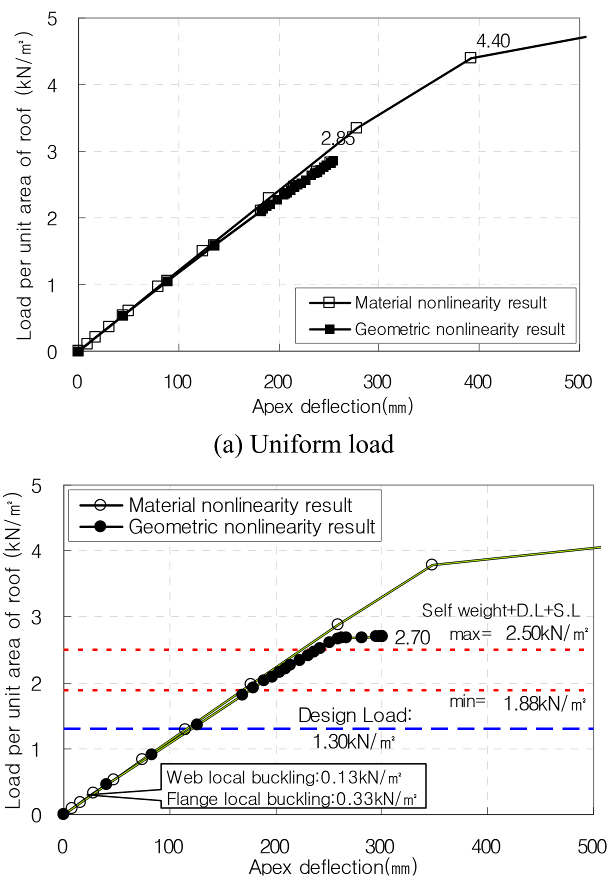
the ANSYS 9.0 (ANSYS 2005) Web local buckling was initially observed at the center of span in Building A and at the columns in Building B.

(2) Lateral torsional buckling
During post-buckling analysis, survey loads were increased at a constant rate. As shown in Fig. 9, lateral buckling was observed under 2.70-2.94 kN/m^2 in Building A and under 2.45- 2.59 kN/m^2 in Building B at where web local buckling was observed previously.

(3) Flange-local buckling
During flange local buckling analysis, survey loads were increased at a constant rate. As shown in Table 3, flange local buckling was observed under 0.33-2.67 kN/m^2 in Building A and under 2.69-2.81 kN/m^2 in Building B at where web local buckling was observed previously.

3.5 Analysis & consequences

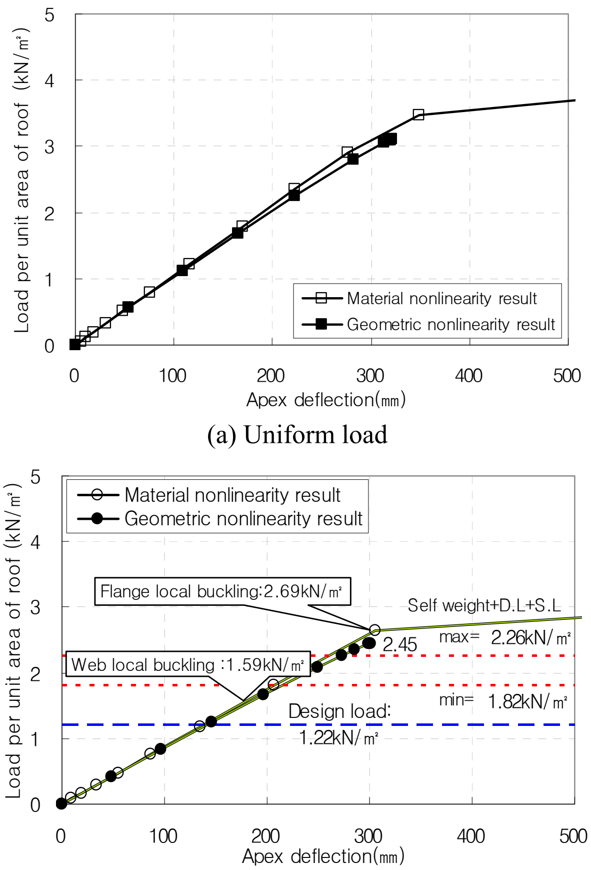
Under uniform load, web local buckling was initially observed and followed by flange local buckling and lateral torsional buckling in Building A and web local buckling was initially observed and followed by lateral torsional buckling and flange local buckling in Building B. However, under survey loads, lateral torsional buckling was initially observed in Building A due



(a) Uniform load

(b) Snow loads

Fig. 12 Results of non-linear analysis for Building A



(b) Snow loads

Fig. 13 Results of non-linear analysis for Building B

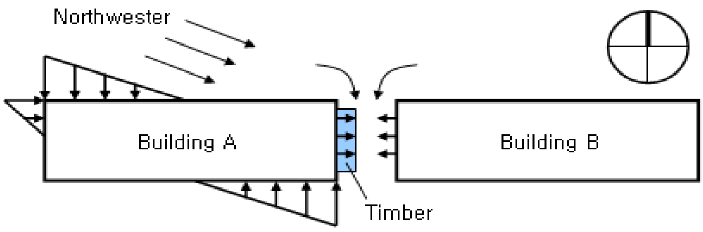
to uneven load distribution and followed by web local buckling and flange local buckling in Building A and flange local buckling was initially observed and followed by web local buckling and lateral torsional buckling in Building B. Therefore, it is deduced that the ultimate load capacity and collapse mode of P.E.B buildings vary significantly depending on load direction and reinforcement type such as flange braces and stiffeners.

4. Suggestions for system improvement

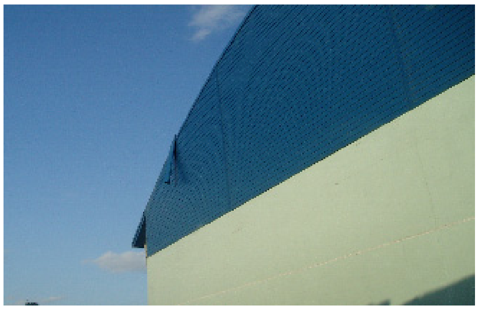
One of the two warehouse buildings built using the P.E.B system in 2003 was completely destroyed and the other was seriously damaged in December 2005. The following is a suggestion for improving the P.E.B system based on the cause analysis and structural safety evaluation.

4.1 Sudden load

The major causes of the collapse and damage were sudden loads such as a heavy snow load and a sudden gust of wind. Snow loads (1.80 kN/m^2 to Building A, 1.64 kN/m^2 to Building B) more



(a) Wind pressure



(b) Parting of finishing material

Fig. 14 The influence of sudden load

than 2.5 times stronger than the design load (0.6 kN/m^2) were applied to the buildings due to a heavy snow which had lasted for approximately one month. Most of the snowfall acted as snow load because only a small amount fell to the ground due to the arch-shaped roofs. In addition, the ventilation monitors at the centers of the roofs prevented the snow from being scattered by wind and even incited the concentration of snow. Consequently, the sectional stress of the members exceeded the permissible stress and caused serious out-of-plane deformation such as web and flange local buckling and lateral torsional buckling. Then, an eccentric load resulting from asymmetric load condition due to wind destroyed one of the buildings.

Therefore, slanted roofs are more appropriate than arch-shaped roofs for the P.E.B warehouse buildings in K City to deal with snow load. When designing a building with an arch-shaped roof, unexpectedly strong snow load and wind load should be taken into consideration. In addition, caution should be exercised when a ventilation monitor is set up at the center of a P.E.B building in an area of heavy snowfall because it may cause sudden load. Therefore, due to the possibility of stronger-than-permissible load concentration associated with climate conditions, the influence of sudden loads should be taken into consideration when determining the shape and size of a P.E.B building.

When the warehouse buildings in K City were built, the MBMA (2002) (Metal Building Manufacturers Association) regulation, the design and manufacturing manual for P.E.B buildings, was applied. As a result, a dead load heavier than that prescribed in the Korean regulation was applied. Though the Korean regulation prescribes that a concentrated load should be applied when live load is not taken into consideration, uniform load was applied in the original structural design. While there was a difference in terms of loading method, structural safety does not seem challenged because a strong live load was applied in the original structural design. Wind load prescribed in ASCE 7-95 (1995) was applied, which differed from that prescribed in the Korean regulation, seemingly because of the difference in reproduction time and evaluation time. Because the influence of wind load may be underestimated if ASCE 7-95 (1995) is applied, it is deduced that applying the Korean regulation is more desirable. In this regard, design formulas should be reviewed and design guidelines should be established.

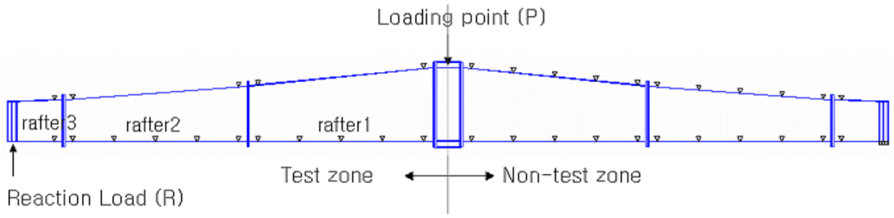
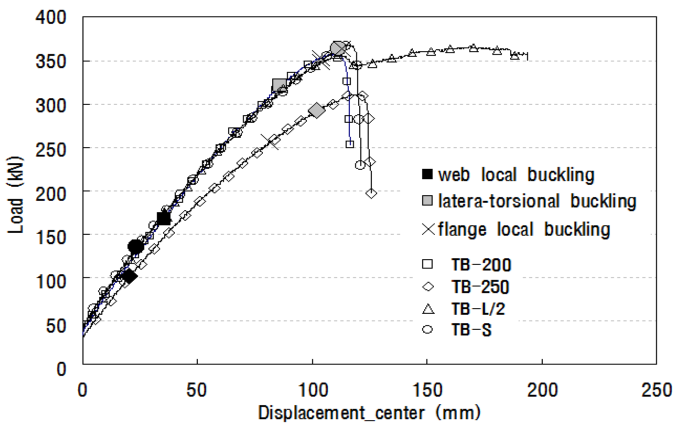


Fig. 15 Specimen (Shim *et al*. 2006, Lee *et al*. 2006, 2009)



(a) Load-Disp relations of specimens

(b) Lateral torsional buckling (TB-250)

(c) Flange local buckling (TB-L/2)

Fig. 16 Test results

Table 4 Test results (Unit: kN)

	Web width-thickness ratio (mm/mm)	Web local buckling load	Lateral buckling load	Flange local buckling load	Ultimate load	Remark
TB-200	200	169	320	352	356	Web width-thickness ratio 200
TB-250	250	105	293	256	311	Web width-thickness ratio 250
TB-L/2	200	174	-	347	364	Unbraced length L/2
TB-S	200	137	361	362	366	Stiffener set up

Fig. 17 End-plate joint used in Korea

4.2 Buckling

Because the rafters used in a P.E.B system are slender, local buckling and lateral torsional buckling are highly feasible depending on the unbraced length. As shown in Figs. 15 and 16 and Table 4, previously conducted studies showed that specimens with a large web width-thickness ratio were vulnerable to web local buckling, lateral buckling and flange local buckling and had the lowest stiffness. Also, a shorter unbraced length (TB-L/2) coincided with better ductility. Therefore, in order to confine lateral buckling completely in a P.E.B system using rafters with tapered webs, the web width-thickness ratio should be small where buckling is expected and the setup angle associated with lateral force and sectional size should be taken into consideration in flange brace design. In addition, the lateral braced length should be short to secure ductility.

4.3 Quality management

Structural analysis programs such as MIDAS have been used for generic steel frame structures and the reliability of their analysis results has been proved by industry experts and researchers. However, the experts of and studies on the programs for the P.E.B system are inadequate. Also, it is sometimes difficult to determine the designer’s intention because the design, production and construction of a P.E.B structure are collectively processed by the program exclusive to the system. Since there is a difference in design and construction methods between P.E.B and generic steel frame structures, design load capacity may not be fully secured if a P.E.B building is constructed in the same way that generic steel frame structures are constructed. Therefore, securing the quality of P.E.B buildings requires educating field staff and technicians and developing shop drawings that can be easily understood by constructors.

Table 5 Comparison of bolted joints

Type	Snug tight	Fully tight
Bolting method	Tightening bolts fully using a wrench	Tightening bolts in accordance with initial design tensile force using torque wrench
Vibration or cyclic load	Can be loosened by vibration or cyclic load	Are not influenced by vibration or cyclic load
Workability	Reduced costs, Can be done easily	Costs more than snug tight, Complicated
Separation displacement	Larger separation displacement under load	Smaller separation displacement under load
Lever reaction	Lever reaction is caused by separation displacement	Plate stiffness reduces lever reaction.

4.4 Joint painting on joints

Bending moment is the major stress at the end-plate and it is delivered by the compressive load capacity of bolts. This type of stress delivery significantly differs from that in friction-type bolted joints of generic steel frame structures. MBMA (2002) prescribes that painting on end-plate joint is allowed if it is a bearing type tension joint, not a friction joint. However, painting on high-tension bolted joints is not allowed in Korea, which causes the problem of rust in case of rain permeating or contact with air. Therefore, the condition of the joint surface of the end-plate used in a P.E.B system is not linked to joint performance and thus painting on joints should be allowed.

4.5 Bolting

MBMA (2002) and AISC (2001) allow a snug tight bolted joint for the end-plate. ASTM defines snug tight bolting as that giving a slight shock with an impact wrench or tightening fully with a spud wrench. Table 5 shows the comparison of a snug tight bolted joint and a high-tension bolted joint.

ASTM did not allow snug tight bolting until 1985. However, its specifications in 2000 allow snug tight bolting. As explained in MBMA (2002), this was because the RCSC (Research Council on Structures Connection) accepted the study result showing that a snug tight bolted joint is as reliable as a high-tension bolted joint. Based on that, the SSTC (Steel Structures Technology Center, Inc.) allows snug tight bolting for end-plates in its Structural Bolting Handbook. Therefore, allowing snug tight bolting does not seem to cause structural problems. Technical studies to verify the reliability of snug tight bolting are needed for its employment.

4.6 Initial web defect

In the P.E.B system, built-up members made by flange-web welding, not single-body type members such as rolled H-shaped steel are used. Welding heat causes the structural defect of initial deformation. Initial deformation at the web may adversely influence the overall structure, so restrictions need to be imposed. Table 6 shows the regulation on web deformation provided by MBMA (2002). However, in Korea, there are no regulations on the initial deformation at the web. Studies and regulations on web initial deformation are needed to prevent the structural defect it causes.

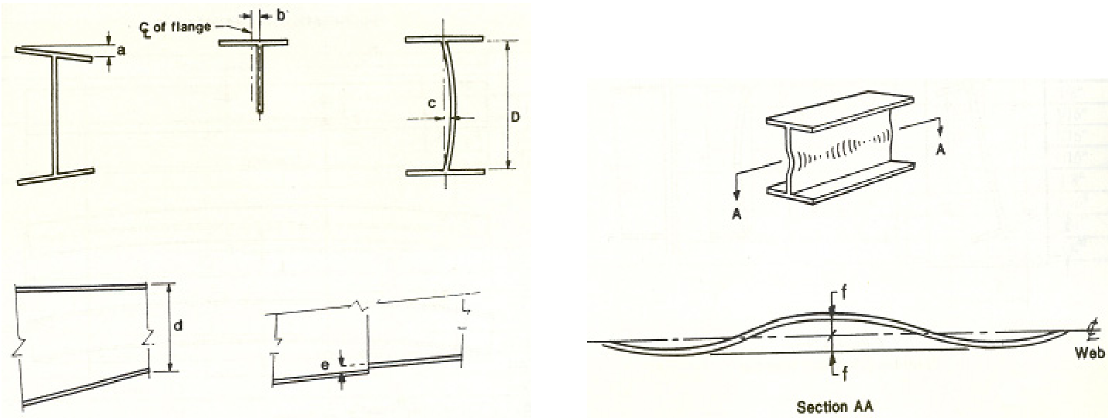


Fig. 18 Web deformation

Table 6 Regulation on web deformation (Unit: mm)

Built-up Structural Members			
	Dimension	Tolerances	
		+	-
Geometry	A	3 -6.35 Max	3 -6.35 Max
	B	6.35	6.35
	D	4.76	4.76
	E	3.18	3.18
	C	1829	
	F	1829	

5. Conclusions

The conclusion of this study based on the structural safety evaluation and structural damage analysis of the P.E.B buildings in K City in order to improve the system and its reliability is as follows.

- When designing a P.E.B building including the decision of its shape and size, the influence of sudden load, concentrated load and wind load associated with climate conditions should be taken into consideration.
- Web width-thickness ratio should be small in the section of rafter with tapered web where buckling is feasible. Flange braces should be designed with setup angle associated with lateral force and sectional size taken into consideration. In addition, lateral braced length of flange braces should be short in order to secure ductility.
- In order to secure the quality of P.E.B structures, training should be provided for field technicians and easy-to-understand shop drawing should be made.
- The condition of end-plate joint surface does not influence its performance, so painting on joints should be allowed.
- Since the defect caused by the initial deformation of web may adversely influence the

overall structure, regulations should be established based on tests and studies.

- Depending on the foreign program exclusive to P.E.B system in the design, production and construction of P.E.B structures has been an obstruction to the advance of Korean technology. Therefore, tests and studies should be conducted in order to properly apply P.E.B system in Korea and develop design programs locally.

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