Influence of Lateral Bracing on Lateral Buckling of Short I-Beams under Repeated Loadings

反復荷重을 받는 짧은 I형 보의 橫座屈에 대한 橫브레이싱의 影響에 관한 考察

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Abstract

Lateral bracing has long been used in design practice to enhance the carrying capacity of the lateral buckling of the beam. Many factors, critically important to lateral bracing performance, do not appear in design formulas. Some of these factors are discussed in this study for the application to short I-beams under repeated loadings through parametric studies with an analytical model : the brace location along the length of the beam, the height of the bracing above the shear center of the beam, and the strength and stiffness of the brace.

The parametric studies are carried out using a propped cantilever arrangement, and also using a geometrically (fully) nonlinear beam model for the brace as well as the beam to capture the system buckling. An idealized bracing system is configured to restrain lateral motion, but not rotation. A multiaxial cyclic plasticity model is also implemented to better represent cyclic metal plasticity in conjunction with a consistent return mapping algorithm.

要 約

보(Beam)의 橫-비틀림 座屈(Lateral-Torsional Buckling)에 대한 抵抗能力을 向上시키기 위해 橫-브레이싱(Lateral Bracing)을 실제 設計에 오랫동안 사용해 왔으나, 橫-브레이싱의 性能에 중요한 因子들은 아직 設計公式에 많이 포함되어 있지 않다. 解析的 모델을 사용하여 아래와 같은 몇개의 因子들에 대한 Parametric Study를 反復荷重을 받는 짧은 I보에 적용하여 그 影響들을 考察하고자 한다 : 브레이스의 보 길이 방향의 位置, 브레이스의 보의 剪斷中心에 대한 높이, 브레이스의 強度와 剛性.

一端固定 他端可動 支持(Propped Cantilever)보를 이용하여 Parametric Study를 遂行하고, 또한 構造物 全體의 座屈現象을 잘 포착하기 위해 보와 브레이스에 幾何學적 (完全)非線形의 보 모델을 사용한다. 여기에서 理想化된 브레이스는 보 斷面의 橫方向의 移動은 拘束하지만 回轉은 자유롭게 하도록 한다. 또한 金屬의 周期的塑性(Cyclic Plasticity)擧動을 보다 잘 나타내기 위해 多軸 周期的塑性 모델을 Consistent Return Mapping Algorithm과 결합시켜 適用한다.

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1. Introduction

The primary mode of respone of the lateral buckling of a beam is lateral motion and rotation of the cross-section. If restraints are added to the system to prevent these motions, while at the same time allowing planar motion, the performance of a torsionally flexible system can be greatly improved. Lateral bracing has long been used in design practice to enhance the carrying capacity of I-beams and other sections which show a propensity toward lateral buckling. Lateral bracing can be realized in a variety of ways, either through the attachment of discrete elements with axes perpendicular to the main member, or through the continuous attachment of a lateral restraining system such as a floor slab. Just as important parameters, such as the height of load in the cross-section, are often not reflected in design formulae, many factors which are critically important to lateral bracing performance do not appear in design formulae. Some of these factors will be discussed herein for application to short beams.

The lateral bracing system is an integral part of the beam/bracing system, and the response will depend upon the interaction of the two components. While this observation is true for all laterally braced systems, it is particularly important for the application to short beams because the inplane forces can be quite large at incipient buckling. Ater buckling, a component of these large forces must be absorbed by the bracing system. If the strength of the brace is not sufficient to resist compressive buckling, then the brace/beam system buckles simultaneously. If the strength of the brace is sufficient to resist the induced forces without buckling, then the beam buckles into a shape which respects the persisting constraint. In many cases it may not be feasible to completely prevent buckling, but it may be important to delay it. We consider only bracing against lateral motion and not against rotation; so even if the brace does not buckle, lateral buckling of the system may be completely prevented.

A number of studies have been made on the effectiveness of various types of lateral restraint and on the strength and stiffness required to inhibit buckling of elastic beams. Mutton and Trahair[5] investigated the stiffness requirements for midspan rotational and translational bracing of perfect, elastic beams acted upon by either top-flange loading or by shear-center loading. Nethercot[6] also studied the effectiveness of translational and rotational restraints on simply supported elastic I-beams, focussing on the relationship between the height of the applied load and the geometric placement of the bracing system. Kitipornchai, Dux and Ritcher[3] investigated the influence of the restraint location along the length of an elastic cantilever beam. Lay and Galambos[4] treated the problem of laterally bracing beams which have a propensity to buckle inelastically, and developed design criteria for cases in which the required plastic strain is high. These rules are based on a rotational capacity consistent with the beam unbrac-ed length slenderness ratio. They calculated a required cross-sectional area for axial strength where the stiffness of brace must be satisfied, and also indicated that flexural strength and stiffness requirements must be satisfied in addition to the axial strength and stiffness when the compression flange is braced. The general issue of lateral bracing requirements remains largely unresolved today, particularly for inelastic buckling.

Hjelmstad and Lee[2] developed a geometrically nonlinear beam model incorporated with a new cyclic plasticity model, which was verified by the same authors[1] to analyze lateral buckling of short I-beam under cyclic loading successfully. A beam model is formulated in terms of stress components and includes superposed infinitesimal transverse warping and torsional warping deformations to treat problems involving high shear and torsion. The kinematic constraint imposed in this model is appropriate for a thin-walled I-section geometry. A multiaxial cyclic plasticity model, incorporating many of the most compelling features of existing phenomenological models, is also implemented to better represent cyclic metal plasticity in conjunction with a consistent return mapping algorithm developed by Simo and Taylor[7], which is suitable for large-scale computation.

2. Analytical Procedure

The effect of adding a discrete translational bracing system, similar to that used in the experiments[2], to the test specimen (propped cantilever beam) is examined analytically. Figure 2.1 shows the position of the brace with respect to the cross-section and with respect to the beam axial coordinate. The lateral bracing arrangement is idealized as shown, enforcing the position of the brace by placing a rigid link between the shear center and the brace point. The influence of the height of the bracing above the shear center of the beam, the location of the brace along the length of the beam, and the strength and stiffness of the brace are examined through parametric studies with the analytical model. Standard values of the test specimen are used as shown in Table 2.1.

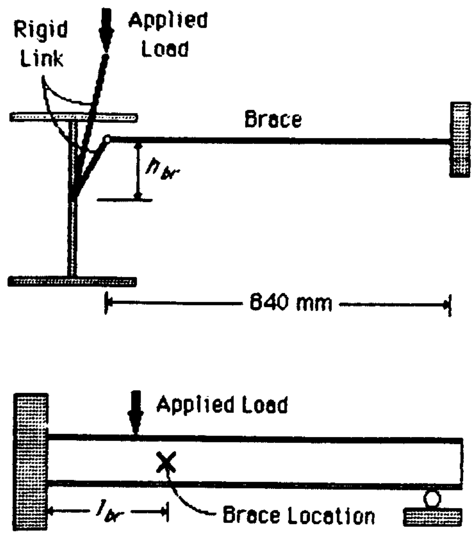

Fig. 2.1 Geometry of the lateral bracing system

Table 2.1 Standard values of test specimen

beam length	2080mm
location of load from fixed end	510mm
height of load above shear center	240mm
eccentricity of load position	0.25mm
depth of cross-section	250mm
width of cross-section	100mm
flange thickness	5.1mm
web thickness	4.6mm
yield strength of material	330MPa
ultimate strength of material	475MPa
fixed end flexibility(w/o load cell)	rigid
right end condition	simple

The brace positions examined in this include h_{br}=110, 95, 70, 45, 0, −45, −70, −95, and −110mm. The height of 95mm (−95mm) corresponds roughly with the brace position used in the experiments, that is, 25mm below (above) the top (bottom) flange. Rectangular tube(box) sections, ranging in area from 20 to 80mm^2, are used here to analytically model the brace. The braces used are 840mm long and quite slender, having $(A/I)_{br}=24$. The location of the brace along the length is varied from $l_{br}=250$ to 1250mm. The brace configurations examined here consist of a brace on only one side of the beam, using a fully nonlinear model for the brace as well as the beam to capture system buckling. The brace is fixed at the end remote from the specimen and pinned to the specimen. The deformation of the system before buckling causes flexure in the brace making it possible to buckle without initial geometric imperfections. The responses are compared to the analytical response of the test beam without bracing.

3. Ananlysis of the Influence of Brace

The parametric study is organized in following way : First the effect of brace location along the length of the beam is examined holding the size and bracing height fixed. The effect of brace size and bracing height are examined for bracing placed at the point of loading. The effect of different brace cross-sectional types is then examined while holding the area of the brace and the location constant. In each case inelastic monotonic and cyclic responses are considered.

3.1 The effect of brace position along the length of the beam

The position of the load along the length of the beam is of fundamental importance to the buckling behavior. There are, of course, many possibilities for bracing arrangements and we will restrict our attention here to a single discrete brace placed somewhere in the span. It is perhaps obvious in the present case, with a single point loading, that the best brace location will be at or near the point of loading. In fact, many design specifications require lateral bracing at points of load (or at points where plastic hinges are likely to form) as a conservative precaution and in lieu of more rigorous knowledge. In this section we demonstrate that the above observation is true and make an effort to quantify the trade-off represented by other bracing locations.

The inelastic monotonic responses of the propped cantilever beam with bracing alternatively at $l_{br}=250$, 375, 500, 625, 750, 1000, and 1250mm are shown in Fig. 3.1 for the brace having area $A_{br}=40\text{mm}^2$ and bracing elevation $h_{br}=95$mm. The response of the beam without lateral bracing is also shown in the figure for comparison. One can observe the clear superiority of bracing in the vicinity of the applied load. Interestingly, the response for bracing up to 250mm past the load point is nearly identical to the response for bracing at the load point. This observation makes sense because the load is located so near to the fixed end. One can also observe that there is virtually no improvement in behavior for bracing locations even moderately remote from the point of loading. In the sequel, the brace will be positioned at the point of loading.

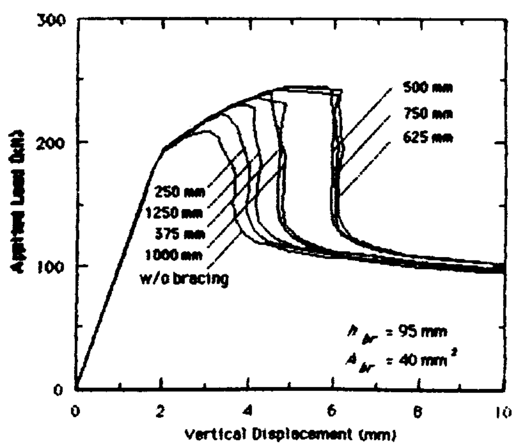

Fig. 3.1 Effect of the position of the load along the length of the beam

3.2 The effect of brace size and elevation with respect to the shear center

The primary parameters studied in this section are the size of the brace and its elevation with respect to the shear center of the cross-section. Since push loading is critical with respect to lateral stability, and since the top flange is in compression for this sense of loading, it is expected that bracing above the shear center will be most effective. We demonstrate the veracity of the previous assertion and make an effort to quantify the importance of this effect. The brace size are chosen to bracket the transition from cases where the brace remains straight while the beam buckles to cases where the brace and beam buckle simultaneously. The parametric domain is covered by alternatively varying brace size and brace dimension with results for both monotonic inelastic buckling and cyclic buckling.

The effect of varying the size of the brace while holding the elevation fixed at 95mm is shown in Fig. 3.2. As the brace size increases both in limit capacity and the vertical deformation capability increase. Braces larger than A_{br}=60mm^2 allow the achievement of the full plastic capacity of the beam in planar bending

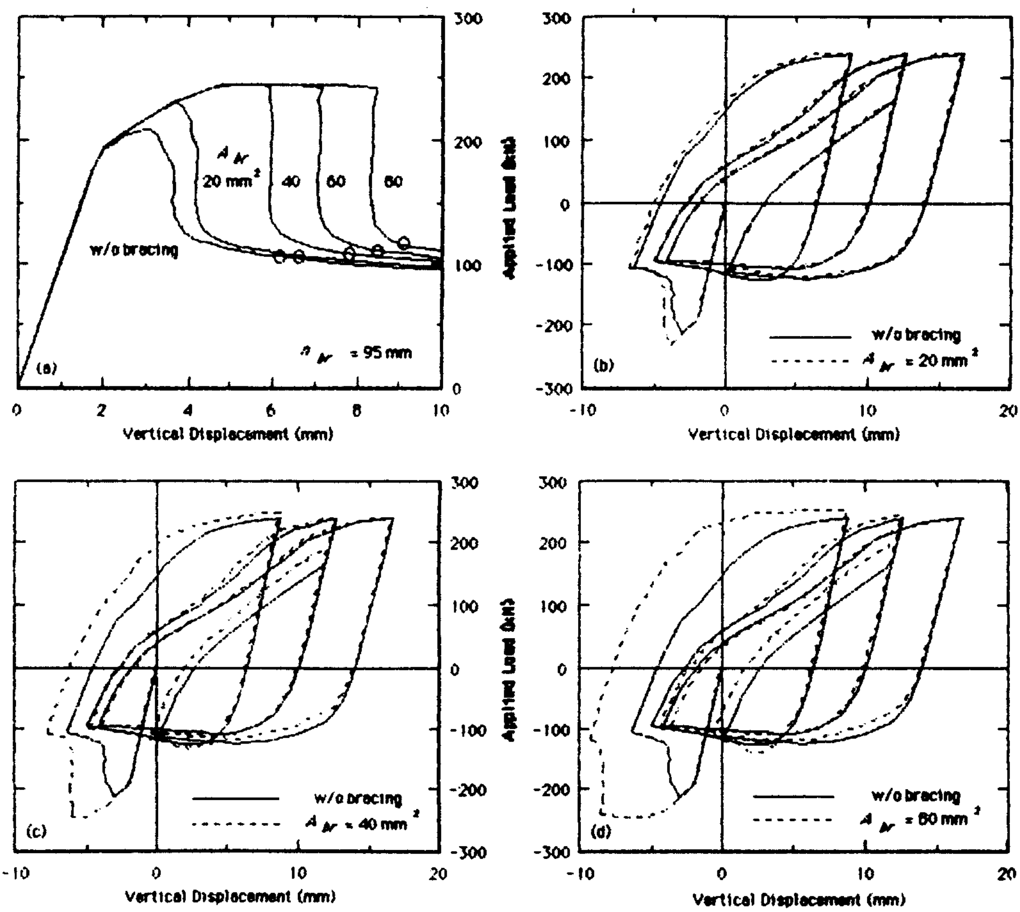

Fig. 3.2 Effect of brace size

before buckling. It is noted that for braces smaller than 60mm^2 the brace buckles in the plane in which it is bending, while those larger do not buckle. It is clear that this type of point bracing will delay but not prevent buckling. The response curves for the cyclic loading cases demonstrate that after buckling the system behaves as if it had not been braced, even for relatively large braces. This same observation was noted in the experiments[2]. The circle symbols(o) on the curves for monotonic loading response represent the points where the load direction is reversed in the first cycle of the cyclic loading.

The effect of varying the elevation of the brace while holding the area fixed at 25mm^2 is shown in Fig. 3.3. In Figs. 3.3(a) one can observe that the system exhibits higher limit loads and has greater vertical deformation capability the higher the brace is placed above the shear center. The brace elevated to 110mm allows the beam to reach its full planar capacity before buckling. In Fig. 3.3(b.c) one can observe the ineffectiveness of bracing below the shear center. The fact that the response for an elevation of −45mm is identical to the response for the system without bracing indicates that during buckling the beams rotates about that point in the cross-section. It is interesting to note that the center of rotation remains fixed even in the presence of progressing inelasticity and large rotations. The cyclic responses again demonstrate the ineffectiveness of bracing in the post-buckling regime.

The combined effects of brace size and elevation are shown again in Fig. 3.4. In each plot, four different bracing sizes, A_{br}=0, 30, 40, 50mm^2, are shown for a single value of the elevation. Each subsequent plot has a lower brace elevation h_{br}=110, 70, 0, −45, −70, −110mm, While this figure presents no new information, it helps to more clearly show the trade-off between brace size and brace elevation. Again, the ineffectiveness of bracing below the shear center is demonstrated.

3.3 The effect of brace cross-sectional geometry

In the previous study the ratio of brace area to moment of inertia was held fixed. In this section we examine braces which have the same cross-section area but have different moments of inertia. Three brace cross-sections are considered as outlined in Table 3.1. The first brace type is the box-section used in the previous study, with a depth of 12.5mm and a wall thickness of 0.8mm. The second brace type is an I-section with considerably larger major moment of inertia, but smaller minor moment of inertia than the box. The third brace type is a smaller box-section with one quarter the moments of inertia of the standard box-section.

Table 3.1 Properties of alternative brace types with equal same brace area (40mm^2)

type	h	b	t	t_f	EI_3	EI_2	GJ
	(mm)				(mm^2−MN)		
box	12.5	12.5	0.8	0.8	220	220	132
I-section	40.0	10.0	0.5	1.0	2240	35	0.7
box	6.25	6.25	1.6	1.6	55	55	33

The monotonic buckling responses with the various braces are given for brace elevations of 110, 70, 0, −45, −70, and −110mm in Fig. 3.5 It is evident from this study that the axial stifness, which is the same for all braces, is not an important influence on the limit capacity and vertical deformation capability of the system. Even through the I-section brace

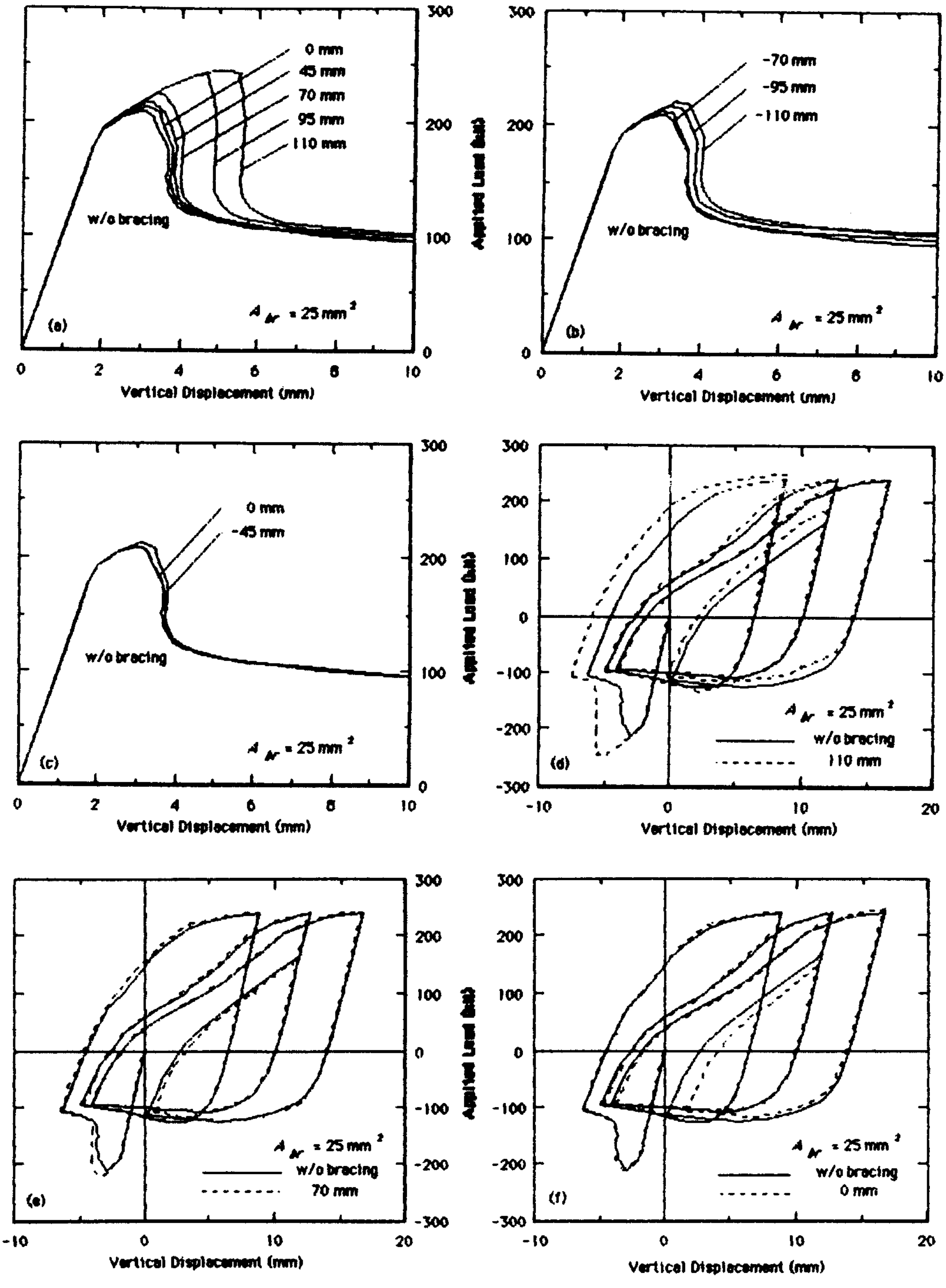

Fig. 3.3 Effect of brace elevation with fixed brace size

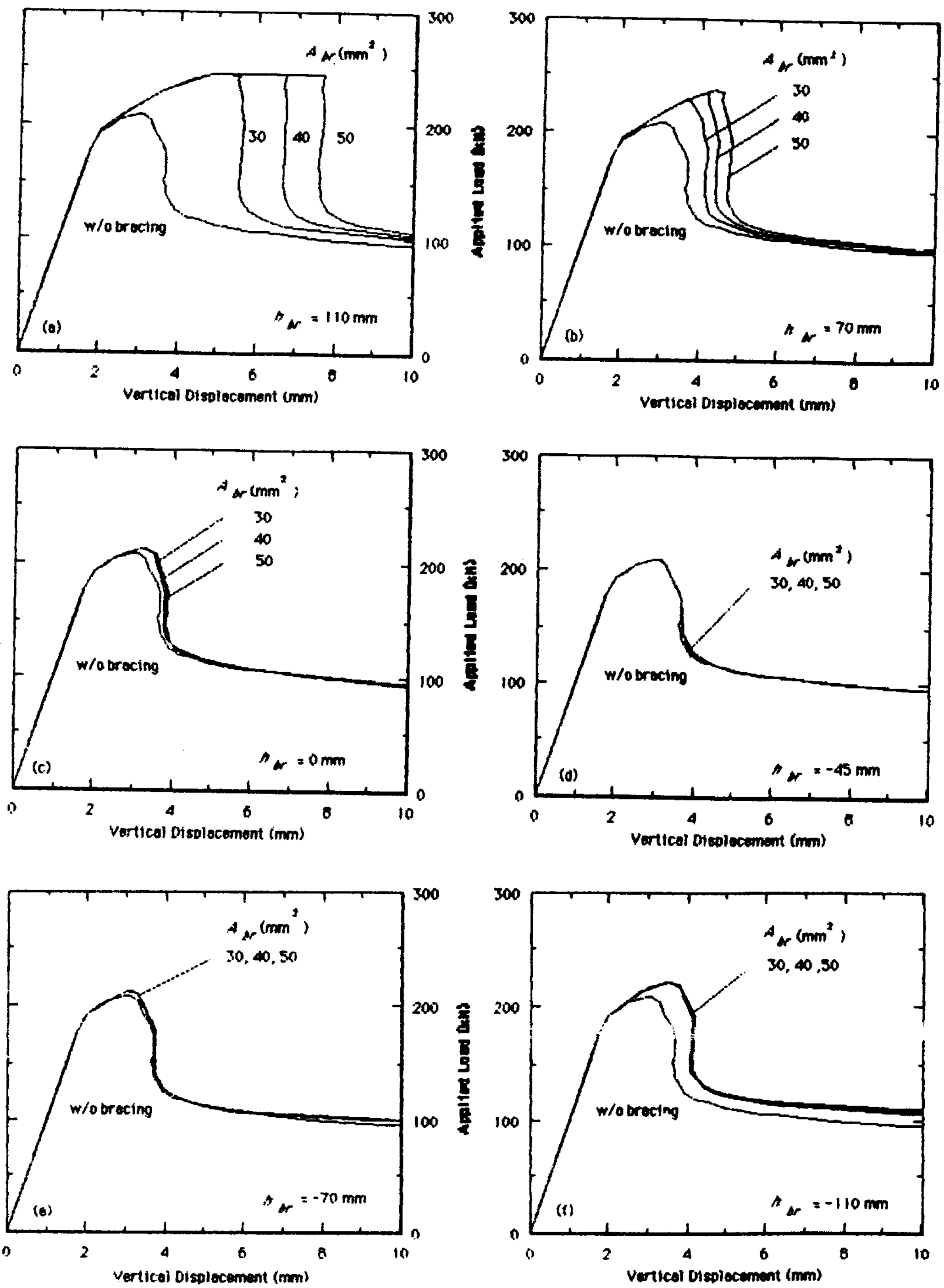

Fig. 3.4 Combined effects of brace size and brace elevation

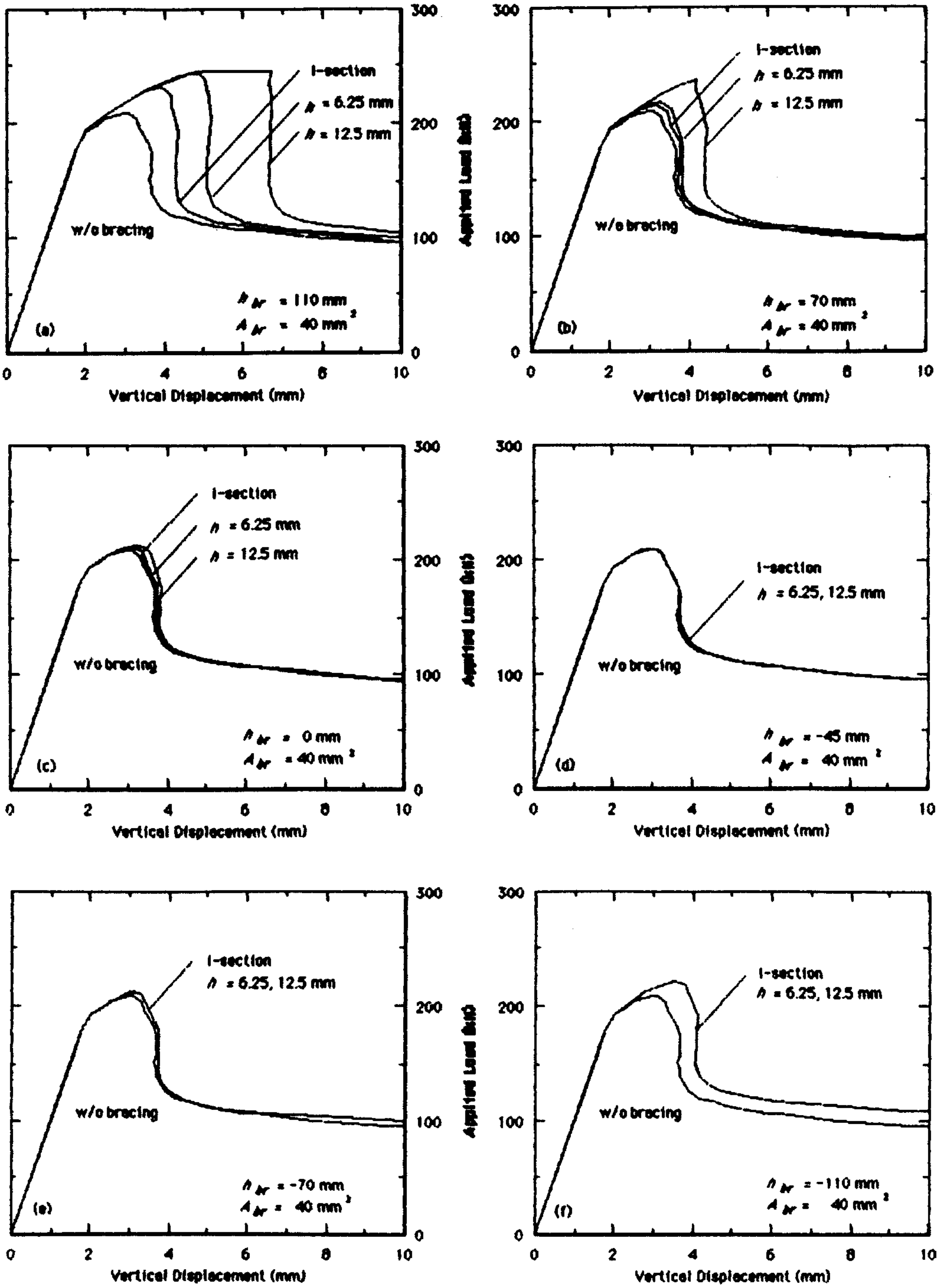

Fig. 3.5 Effect of different brace geometries

had the largest major flexural moment of inertia it buckled the soonest, because buckling in the minor direction occurred even before the beam buckled laterally. One can conclude that the limit load of the beam-brace system depends most significantly on the minor moment of inertia of the brace.

4. Conclusion

Lateral bracing is clearly effective in delaying buckling, but it does not necessarily prevent it and it has little impact on the post buckling response. The most desirable location to brace along the beam is at or near the position of the applied load. The best level to place translational bracing in the cross-section of beam is near the flange that is compressed by a push loading (the top flange in the experiments). Bracing placed below the shear center has little effect on lateral buckling. The center of rotation of the beams studied here was near 50mm below the shear center, and remained fixed during lateral buckling, as evidenced by the ineffectiveness of bracing placed there.

Flexural rigidity and axial strength of the bracing is important to the lateral buckling of beam. Increasing the flexural and axial stiffness has a great effect on the lateral buckling of beam when the level of bracing is near top flange. Minor flexural stiffness of bracing is also important parameter to the buckling response because simultaneous brace buckling seems to cause the greatest difference in behavior. It is clear from these studies that the brace size should, at the very least, depend on the position of the load and the position of the bracing in addition to the strength and stability properties of the beam.

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