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Seismic Performance of Multistorey Steel Buildings with Different and Hybrid Bracing Configurations: A Critical Review

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***Abstract* – Bracing is the most common means of stiffening multistorey steel buildings against earthquakes, yet published comparisons of brace geometry are hard to combine because each rests on its own building, design basis, analysis procedure and response measure. This paper critically reviews, in narrative form, twenty-nine studies of braced steel frames and of incremental dynamic analysis (IDA). The studies are grouped into comparisons of conventional geometries, eccentric and strongback systems, hybrid systems, and IDA-based work, and are compared in terms of building height, analysis level and the response quantities each reports. The literature agrees that bracing reduces drift and displacement relative to an unbraced frame. It does not agree on which geometry is best: the favoured arrangement changes with building height, analysis procedure, response measure and the importance given to cost or collapse. Hybrid bracing has been developed mainly by combining components or devices, such as buckling-restrained braces with self-centring or friction elements, whereas combinations of brace geometries within one building have received little attention. Where IDA is used, each building usually carries a single brace layout. Four research gaps are identified, and the design of a controlled study that would address them is outlined: one building, one design basis, one ground-motion set, IDA, and several response measures with their uncertainty reported.**

Keywords* – *Steel braced frames; brace configuration; hybrid bracing; incremental dynamic analysis; interstorey drift; seismic performance; critical review

I. INTRODUCTION

Multistorey steel buildings owe much of their efficiency to the slenderness of their members, but the same slenderness makes a moment-resisting frame flexible, so that lateral drift rather than strength often governs design in earthquake-prone regions. Bracing is the usual remedy. A diagonal member turns part of the lateral load into axial force, which steel carries efficiently, and a braced bay then acts as a vertical truss that stiffens the building and limits its drift. How well it does so depends on how the braces are arranged. Concentric systems include X, single and double diagonal, V and inverted-V (chevron), K, knee, zipper, and multistorey or mega arrangements. Eccentric systems offset the braces so that a short link beam yields and dissipates energy while the braces remain largely elastic.

Researchers have compared these arrangements for many years, yet the results do not point to a single answer. Among the studies reviewed here, X bracing gave the lowest displacement in one-storey industrial frames [1], inverted-V bracing the lowest displacement and weight in a ten-storey building [2], K bracing the least displacement in a sixty-storey building [3], and knee bracing the lowest roof displacement and acceleration in irregular frames [4]. These findings describe different buildings, loads, analysis procedures and response measures, so they cannot simply be ranked against one another.

The word hybrid adds a second source of confusion. It has been used for combinations of bracing devices, such as buckling-restrained braces (BRBs) with self-centring or friction elements, or shape memory alloy cables with viscoelastic dampers [5]–[9], for strongback systems that couple braces with an elastic spine [10], [11], and, more loosely, for the use of different brace geometries within one structure. The first two meanings are well represented in the literature. The third bears most directly on the practical question of which geometry to place where, yet it appears least often.

Seismic performance also depends on the intensity of shaking. Incremental dynamic analysis (IDA) scales a set of earthquake records through increasing intensity until the structure approaches collapse [12], [13], and so shows how response develops from elastic behaviour to instability. That makes it well suited to comparing brace arrangements across intensity levels. It has been applied to braced frames [7], [10], [14]–[17], but seldom to compare arrangements under common conditions.

The review aims to do four things. It sorts the studies by bracing system, building height and analysis method. It sets their findings side by side for each response parameter, to show which conclusions survive a change of building or method. It derives the research gaps concerning brace geometry, hybrid bracing and IDA. And it draws out what those gaps mean for the design of future comparisons. The method is described in Section II, the underlying mechanics in Section III and the studies themselves in Section IV. Sections V and VI compare and combine their findings, Section VII sets out the gaps, Section VIII turns them into design requirements and Section IX concludes.

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II. REVIEW METHOD AND SCOPE

This is a narrative review written from a critical standpoint, not a systematic one: no formal protocol such as PRISMA was applied. Three questions guided the review. First, which effects of bracing on drift, displacement, base shear and cost are reported consistently? Second, where do the reported effects differ, and can the differences be traced to the building, the assumptions or the method? Third, what has not yet been examined about combining brace geometries in one multistorey steel building and assessing it across a range of shaking intensities?

The studies come from the literature survey carried out for the first author's M.Tech dissertation and were sorted into three groups: comparisons of conventional bracing geometries, hybrid and special bracing systems, and work that uses or develops IDA. A source was kept when it appeared in a journal or conference proceedings with a bibliographic record that could be confirmed, concerned braced steel frames or IDA methodology, and gave at least one seismic response quantity or analysis procedure. Twenty-nine sources remain, published between 2002 and 2025.

Every study was classified by building height, bracing system, analysis procedure, ground-motion input and response quantities. The figures quoted are those given by the original authors, and they hold only for the buildings, loads and codes those authors used. The sample is not exhaustive. Sources whose records could not be confirmed were not used, which probably favours open-access and conference papers, and the comparisons should be read with that bias in mind.

III. MECHANICS OF BRACED FRAMES AND OF IDA

A. Brace Geometries and Load Paths

In an X-braced bay two diagonals cross at mid-height. Under either direction of load one is in tension and the other in compression, so the bay stiffens the frame symmetrically; the compression diagonal may buckle, after which the tension diagonal carries most of the load. In V and inverted-V (chevron) bays the braces meet at the beam. When the compression brace buckles, the tension brace pulls on the beam with an unbalanced vertical force, so beam design and post-buckling storey drift matter. K bracing meets at the mid-height of a column, so that buckling of a brace loads the column laterally, which has made it unpopular in seismic design, although some of the reviewed studies report favourable results for it [3], [15]. Knee bracing connects a short diagonal to a beam-column joint and leaves the bay open, with part of the energy dissipated in the knee element. Zipper bracing adds vertical members at the chevron apexes to share the unbalanced force between storeys and spread yielding over the height. Multistorey-X and mega bracing span several storeys and form a stiff global truss from fewer, longer members (Fig. 1).

Eccentrically braced frames (EBFs) connect the braces away from the joint so that a short link beam yields while the braces are protected. Strongback systems add a stiff, nearly elastic vertical truss to a braced frame, so that drift is spread more evenly and a single weak storey is less likely to form [10], [11]. Off-centre bracing [18] replaces the straight diagonal with a bent one, whose midpoint is tied back to a corner joint by a low-stiffness member, which introduces a controlled geometric nonlinearity. The common thread is that geometry decides where the brace forces enter the frame, which member yields first and how the damage is spread over the height. Those effects are what the comparative studies try to measure.

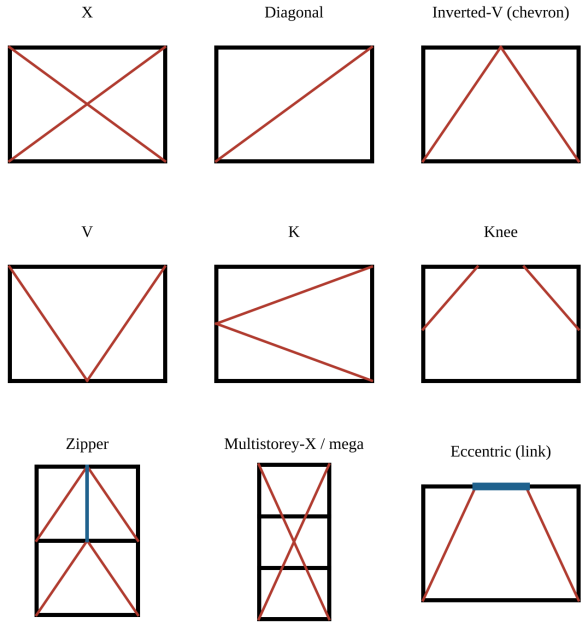


Fig. 1. Brace geometries considered in the reviewed studies (schematic elevations, not to scale).

B. What Hybrid Means in the Literature

Four meanings of hybrid bracing appear in the reviewed work. The first is a device hybrid, in which two energy-dissipating or self-centring components are combined in one brace, for example BRB with self-centring viscous elements [6], shape memory alloy (SMA) cables with viscoelastic dampers [7], a BRB in series with a friction damper [8], or an Fe-SMA core [9]. The second is a system hybrid, in which braces or links are coupled with an elastic spine [10], [11]. The third is a hybrid in the vertical distribution of brace technologies, as when BRBs are placed in the lower storeys and conventional braces above them [5]. The fourth, which this review calls hybrid geometric bracing, uses two or more conventional brace geometries in one building, for example X bracing in some storeys and chevron bracing in others, different geometries in different bays, or X, K, V and chevron bracing together in one building (Fig. 3). The distinction matters because the first three change what the brace is made of, whereas the fourth changes only where the load enters the frame.

C. Incremental Dynamic Analysis

In IDA a structural model is analysed under each record of a ground-motion suite, with the record scaled upward through a series of intensity levels. Each run produces a point on a curve relating an intensity measure, commonly the first-mode spectral acceleration at 5% damping, to a damage measure such as maximum interstorey drift [12], [13]. The family of curves is summarised by its median and by fractiles, and limit states such as the onset of collapse can be read from each curve. Because the scatter between records is large, the number of analyses is also large: one of the reviewed studies required 5,040 nonlinear analyses for eighteen frames [16]. IDA has also been combined with bootstrap statistics to separate the

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effect of a design change from record-to-record variability [19], and with Monte Carlo sampling to show how uncertainty in member parameters alters the result [20].

IV. REVIEW OF THE LITERATURE BY THEME

A. Comparisons of Conventional Bracing Geometries

The simplest comparisons use code-based static analysis. In one-storey industrial frames with three bay lengths, Gurung et al. [1] found X bracing best for displacement and period but highest for base shear, and found that bracing alternate bays also helped. Sheen et al. [21] compared X, diagonal, knee, V and chevron bracing in an irregular eight-storey frame using static, response-spectrum and pushover analysis, and reported X and chevron bracing as the better options, with chevron the more economical and better in the nonlinear range. Kulkarni and Joshi [2] designed a ten-storey frame to Indian provisions and found inverted-V bracing gave the smallest displacement along the longer plan direction and the smallest weight of the braced options. Siddiqi et al. [3] examined a sixty-storey frame under wind and gravity only, with K bracing giving the least displacement and double diagonal bracing the least steel, especially in central bays. Mahdavi et al. [4] used nonlinear time-history analysis with eleven records on irregular frames of five, eight and eleven storeys. They found knee bracing best for roof displacement and acceleration and inverted-V bracing best for first-storey column shear.

Studies that use nonlinear analysis over a wider range of heights reach orderings that differ again. Nassani et al. [22] analysed frames of four to sixteen storeys by pushover and time-history analysis and found that bracing cut interstorey drift by about 58% on average, with inverted-V, V and zipper layouts favourable for displacement and drift. Patil and Sangle [23] found chevron, V and zipper bracing beneficial in pushover analysis of frames of fifteen to thirty-five storeys, and noted the influence of building height and load pattern. Yang et al. [24] compared five layouts in a five-storey office building at three hazard levels with cost included: a multistorey-X frame used about 20% less steel than an inverted-V frame and was the cheapest over its life cycle, while the X frame, though low in lower-storey drift, was the most expensive. Abdulhameed et al. [25] compared ten layouts of a sixteen-storey building at approximately equal bracing weight under one record, and reported that mega-X bracing in a diamond pattern reduced roof displacement by about 48% and 44% in the two plan directions. Di Sarno and Elnashai [26], retrofitting a nine-storey frame, found that mega-bracing reduced mean interstorey drift by about 70% relative to the original frame and used roughly 20% less steel than special concentric bracing, while buckling-restrained mega-braces performed slightly better but needed more steel. Estekanchi et al. [18] reported response reductions of up to about 2.5 times with off-centre bracing relative to X bracing in frames of two to six storeys, together with larger lowest-storey drift. Cui and Liu [27], in shaking-table tests and finite-element analysis of a spatial frame, found that bidirectional X bracing improved stiffness and response over unidirectional bracing, although the numerical error exceeded 20% under severe excitation.

B. Eccentric and Strongback Systems

Liu et al. [15] analysed eccentrically braced frames of three, five and eight storeys with K, V and D link arrangements, using pushover, time-history and loss assessment. K bracing gave the highest capacity and stiffness, whereas V bracing gave the lowest expected loss. Acosta et al. [14] applied IDA to EBFs of five, ten and fifteen storeys with four brace layouts and found that two of them, Diagonal_1 and inverted-V, controlled peak drift better than the V layout, with demand concentrated in the lower storeys. In strongback frames of six and twelve storeys, Salek Faramarzi and Taghikhany [10] found through IDA that an X layout with the brace intersection at two-thirds of the beam length gave the greatest ductility and the smallest chance of collapse, while the chevron layout was the least ductile. Soleymani and Saffari [11] proposed a strongback system with shear links, which reduced drift concentration and spread inelastic deformation more evenly over the height; a link length ratio of 0.2 gave the best results of the cases examined.

C. Hybrid Bracing Systems

Chao et al. [5] installed BRBs in the lower storeys of three- and six-storey frames, with conventional hollow-section braces above, and found that BRBs in only a few of the lowest storeys gave performance comparable to BRBs throughout, while delaying or preventing fracture of the conventional braces. This is the closest reviewed example of distributing different brace types along the height, but the variable is the brace technology and not the geometry. Freddi et al. [28] tested a two-storey frame retrofitted with external BRBs and found that column distortion limited their effectiveness, which restraining the columns reduced.

The remaining hybrid studies combine components. Yan et al. [6] combined BRBs with self-centring viscous braces, controlling the energy shared between the two through a design factor, and obtained frames that met their performance targets and controlled floor acceleration better than either system alone. Shi et al. [7] combined SMA cables with viscoelastic dampers in the same brace, ran IDA with forty-four far-field records on five frames, and found that the dampers kept working after the cables failed, which reduced drift, residual drift and acceleration. Zhai et al. [8] put a BRB in series with a friction damper, reducing the risk of brace failure under extremely rare earthquakes. Jena et al. [9] showed that Fe-SMA buckling-restrained braces left much smaller residual drift than steel BRBs of either conventional or hybrid type, with rigid connections giving the smallest drift. Moradi et al. [17] found that SMA braces reduced maximum drift and permanent roof displacement more than BRBs in a four-storey frame, although the SMA response depended more strongly on the spectral content of the records.

D. Post-Earthquake Damage Assessment

Makarios et al. [29] approached braced frames from the side of assessment and not design. Their "M and P" technique combines a measured fundamental frequency with the frequency-roof displacement relation from a pushover analysis to find the roof displacement that matches the damage state of an existing frame, and then checks the result against the degraded stiffness matrix. Demonstrated on a six-storey frame with X or V bracing, it identified the location and severity of seismic damage without needing the excitation record. It does not compare brace arrangements and so does not enter the comparisons that follow.

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E. Studies Using Incremental Dynamic Analysis

The foundational IDA papers set out the method and its summary statistics for single- and multi-degree-of-freedom models [12] and applied it to a nine-storey moment frame with twenty records [13]. Fragiadakis et al. [19] used IDA with bootstrap statistics to show that the effect of vertical irregularity on a nine-storey frame depended on its type and location, and Vamvatsikos and Fragiadakis [20] showed that uncertainty in beam-hinge parameters changed the estimated performance of a steel frame. The braced-frame applications are limited. Asgarian and Jalaeefar [16] used IDA on eighteen X-braced and chevron-braced frames designed to three editions of the Iranian code, and found that chevron frames generally controlled displacement better than X frames and that frames designed to the earliest edition were markedly more vulnerable. Moradi et al. [17] compared four brace geometries equipped with SMA or BRB elements. The IDA studies on EBFs, strongback frames and self-centring braces [7], [10], [14], [15] each assign a single layout to every model.

V. COMPARISON OF THE REVIEWED STUDIES

Table I summarises the buildings, systems, analyses and response measures of the reviewed studies. The sample spans buildings from one storey to sixty (Fig. 2), analysis from linear static to IDA and shaking-table testing, and response measures from displacement and weight to collapse probability and monetary loss. Only a minority of studies use IDA, and those that state the building height are concentrated in buildings of fifteen storeys or fewer.

TABLE I. PRINCIPAL REVIEWED STUDIES

Ref.	Building or model	Bracing system	Analysis	Response measures
[1]	One-storey industrial frames	Diagonal, K, X	Linear static	Displacement, period, base shear
[2]	G+9 frame	X, V, inverted-V, knee	Code-based static	Displacement, weight
[3]	60-storey frame	Single and double diagonal, K, V, knee	Wind and gravity loading	Displacement, steel weight
[4]	5-, 8-, 11-storey irregular frames	Gate, inverted-V, knee	Time history, 11 records	Roof displacement, acceleration, column shear
[5]	3-, 6-storey frames	BRBs low, hollow-section braces high	Time history	Drift, brace fracture, BRB distribution
[6]	4-, 8-, 12-storey frames	BRB with self-centring viscous brace	Pushover; time history	Peak and residual drift, floor acceleration
[7]	Five frames	SMA cable with viscoelastic damper	IDA, 44 far-field records	Drift, residual drift, acceleration, risk measures
[8]	9-, 20-storey frames	BRB in series with friction damper	Static; dynamic	Performance objectives, collapse risk
[9]	3-, 9-, 20-storey frames	Fe-SMA BRBs	Time history, 20 far-field and 20 near-fault pairs	Peak and residual drift
[10]	Strongback frames, 6, 12 storeys	Vertical truss variants	Static; IDA	Ductility, overstrength, collapse fragility
[11]	6-storey frames	Strongback with shear links	Cyclic pushover; time history	Drift, energy dissipation
[14]	EBFs, 5, 10, 15 storeys	Four EBF layouts	IDA, 20 records	Peak and residual drift, link rotation
[15]	EBFs, 3, 5, 8 storeys	K, V, D links	Pushover; time history; IDA-based fragility; loss assessment	Capacity, stiffness, expected loss
[16]	5-, 8-, 12-storey frames	X, chevron	IDA, 20 records	Stiffness, drift, displacement, capacity
[17]	4-storey frame	SMA and BRB in four geometries	IDA, 20 records	Maximum drift, permanent roof displacement
[18]	2-, 4-, 6-storey frames	Off-centre bracing vs X	Pushover; time history, 3 records	Base shear, acceleration, drift
[21]	G+7 irregular frame	X, diagonal, knee, V, chevron	Static, response spectrum, pushover	Displacement, drift, brace weight
[22]	4- to 16-storey frames	X, V, inverted-V, knee, zipper	Pushover; time history	Capacity, drift, damage index
[23]	15- to 35-storey frames	Chevron, V, X, zipper	Pushover, several load patterns	Displacement, drift, base shear, performance point
[24]	5-storey office building	Inverted-V, V, X, multistorey-X, zipper	Time history, 3 hazard levels	Drift, acceleration, repair, life-cycle cost
[25]	16-storey frame, equal bracing weight	X, inverted-V, mega-X, diamond	Time history, 1 record	Roof displacement, drift, base shear and moment
[26]	9-storey retrofit	Special concentric, BRB, mega-braced	Inelastic time history, 3 hazard levels	Drift, plastic rotation, steel weight
[27]	Spatial frame, scaled model	Unidirectional and bidirectional X	Shaking table; finite element	Frequency, damping, acceleration, displacement, strain
[28]	2-storey frame, retrofit	External BRBs	Pseudo-dynamic hybrid test; finite element	Drift, column deformation

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Ref.	Building or model	Bracing system	Analysis	Response measures
[29]	6-storey frame	X or V	Monitoring with pushover (M and P)	Eigenfrequency, roof displacement, stiffness degradation

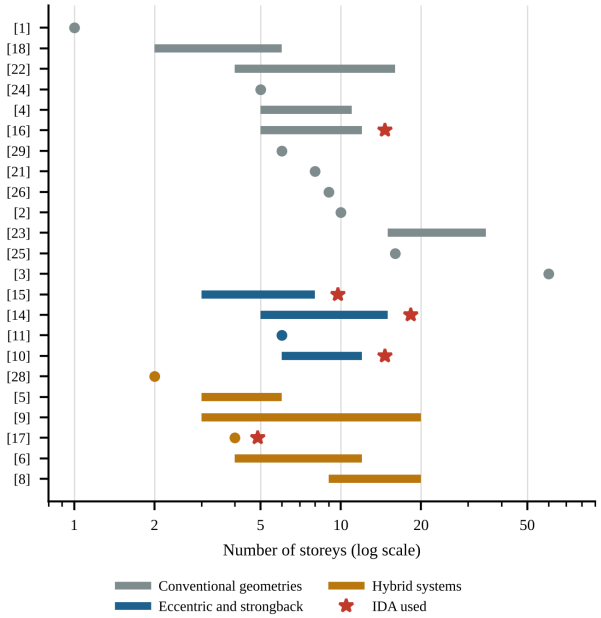


Fig. 2. Storey range of the reviewed building models, by group. Studies that use IDA are marked. Studies [27] and [7] are not shown because the number of storeys is not stated.

Table II lists the geometry reported as favourable in the comparative studies. No geometry is favoured consistently. X bracing leads in some studies [1], [21], inverted-V in others [2], [14], K [3], [15], knee [4], chevron [16], multistorey-X [24] and mega-X with a diamond pattern [25]. Even where studies share a geometry, the reported advantage is conditional. Chevron bracing outperformed X on displacement in [16], yet gave the lowest ductility and highest collapse probability among strongback layouts in [10]; the two results concern different systems and measures. V-shaped EBFs gave the lowest expected loss in [15] but larger drift than the Diagonal_1 and inverted-V layouts in [14]. Under equal bracing weight, mega-inverted-V gave slightly lower roof displacement in one plan direction and mega-X in the other [25].

TABLE II. CONFIGURATIONS REPORTED AS FAVOURABLE IN COMPARATIVE STUDIES

Ref.	Basis of comparison	Configuration reported as favourable (measure)
[1]	One-storey frames; code-based	X (lowest displacement and period; higher base shear)
[2]	G+9 frame; code-based static analysis	Inverted-V (lowest displacement in the X direction; lowest weight among braced options)
[3]	60-storey frame; wind and gravity	K (least displacement); double diagonal (least steel)
[4]	5-, 8-, 11-storey frames; time history	Knee (roof displacement, acceleration); inverted-V (column shear)
[10]	Strongback frames; IDA	X with intersection at two-thirds of the beam (highest ductility); chevron (lowest ductility)
[14]	EBFs of 5, 10, 15 storeys; IDA	Diagonal_1 and inverted-V (peak drift)
[15]	EBFs of 3, 5, 8 storeys; pushover, time history, loss	K (capacity, stiffness); V (lowest expected loss)
[16]	Frames of 5, 8, 12 storeys; IDA	Chevron (larger displacement reduction than X)
[21]	G+7 irregular frame; static and pushover	X (lower drift); chevron (better nonlinear response; about 65% of the weight of X)
[24]	5-storey frame; three hazard levels	Multistorey-X (lowest life-cycle cost); X (highest life-cycle cost)
[25]	16-storey frame; equal weight; one record	Mega-X with diamond pattern (roof displacement and drift)

Table III collects the findings by response parameter and shows where agreement ends. It also shows that the parameters on which agreement is strongest (drift and displacement reduction relative to an unbraced frame) are those on which the studies least discriminate between geometries.

TABLE III. CONSISTENCY OF REPORTED FINDINGS BY RESPONSE PARAMETER

Parameter	Where studies agree	Where they diverge	Studies
Drift and displacement	Any bracing reduces drift and displacement compared with an unbraced frame	Which geometry gives the least: X, inverted-V, K, knee, chevron, V, zipper, multistorey-X or mega-X	[1]–[4], [21]–[25]

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Parameter	Where studies agree	Where they diverge	Studies
Base shear and force demand	Bracing stiffens the frame and changes force demand	X gave the highest base shear in [1]; off-centre bracing and a mega layout lowered it in [18], [25]; column shear ranked inverted-V first in [4]	[1], [4], [18], [25]
Steel weight and cost	Layout changes steel quantity and cost	Lightest: inverted-V [2], double diagonal [3], multistorey-X [24], mega-bracing [26]; X had the highest life-cycle cost [24]	[2], [3], [21], [24], [26]
Capacity, ductility and collapse	Link yielding in EBFs and a stiff spine in strongback frames improve behaviour	K highest capacity but V lowest loss [15]; chevron lowest ductility [10] but better displacement control than X [16]	[10], [11], [14]–[16]
Residual drift and floor acceleration	Self-centring and SMA elements reduce residual drift	Size of the benefit depends on record frequency content [17] and connection type [9]; rarely reported for geometry comparisons	[6], [7], [9], [17]

VI. SYNTHESISED FINDINGS

Three findings hold across the studies. First, bracing of any type reduces drift and displacement compared with an unbraced frame [2], [4], [21]–[23]. Second, the way braces are arranged changes steel quantity, cost and the distribution of damage over the height [2], [3], [24], [26]. Third, systems that concentrate yielding in links improved energy dissipation [15], and those that add a stiff spine spread inelastic demand more evenly over the height [10], [11].

The studies disagree on which geometry is best, and the disagreement has identifiable sources. The buildings differ in height, from one storey [1] to sixty [3], and in regularity. The design basis differs, whether Indian, Bangladeshi, Iranian or Canadian provisions or none, as in a study of wind and gravity only [3]. The analysis differs in level, from code-based static analysis [1], [2], [21] through pushover [23] and single-record or few-record time history [18], [25] to IDA [10], [14], [16]. The response measures differ: drift or displacement in some studies, steel weight, collapse probability or monetary loss in others. Because height, code, loading, modelling platform and measure change together, the ranking of a geometry cannot be separated from the context in which it was obtained.

Intensity adds a further dependence. Drift reduction by SMA braces relative to BRBs differed among four geometries at the higher intensity examined, while SMA frames showed larger median drift at the lower intensity [17]; the influence of vertical irregularity in a nine-storey frame depended on its type, its location and the shaking level [19]; and the first-storey drift ordering of five layouts differed between two hazard levels [24]. The evidence is not uniform, as the ordering of EBF layouts stayed the same across intensity in the five- and ten-storey frames of [14]. Still, a single-intensity comparison does not show which arrangement keeps its advantage as shaking increases.

Hybrid bracing has advanced mainly through components. The benefit in drift, residual deformation and collapse resistance is attributed to the added devices [5]–[9], with brace geometry held constant or varied uniformly over the building. The studies cannot show whether combining geometries in one building gives gains of its own, or penalties such as drift concentrated in a single storey.

VII. RESEARCH GAPS

A. Conflicting Evidence on Brace Geometry

Studies that compare single geometries do not agree on a preferred option (Tables II and III), and the comparisons differ in building, code, loading, platform and measure. A like-for-like comparison, in which one building, one design basis, one ground-motion set and the same response measures are applied to every arrangement, is still lacking in the reviewed work.

B. Hybrid Bracing Concentrates on Mechanisms, Not Geometry

Where bracing types have been combined within one structure, the combination has been one of mechanisms or devices [5]–[11]. Studies that vary geometry within a building are limited to bay placement and the distribution of bracing [1], [3], [25], to bidirectional versus unidirectional X arrangements [27], or to whole-building layouts compared one at a time [14], [16], [17], [22]–[24]. Brace type, combination and location have therefore been examined separately and not as joint variables. To the authors' knowledge, no study has evaluated mixed conventional brace geometries within a single building under IDA.

C. Intensity Dependence and Limited Use of IDA

Many geometry comparisons rest on code-based static or response-spectrum analysis [1]–[3], [21], on pushover analysis alone [23], or on time history with a single record [25] or three normalised records [18]. These describe response at one or a few intensity levels, yet rankings can change with intensity [17], [19], [24]. IDA has been applied to X and chevron layouts [16], EBF variants [14], [15], strongback systems [10], SMA and BRB frames [17] and self-centring hybrid braces [7], but each building carries one brace layout.

D. Response Measures, Uncertainty and Modelling Fidelity

Geometry comparisons most often report displacement, drift, base shear or steel weight [1]–[3], [21], [22], whereas residual drift, collapse capacity and monetary loss appear mainly in studies of special systems or individual buildings [6], [7], [9]–[11], [14], [15], [17], [24]. Differences between layouts can be small relative to the scatter: in one equal-weight comparison the two best layouts differed by about 1% in roof displacement under a single record [25]. Bootstrap confidence intervals were used to test significance in only one of the reviewed IDA studies [19], and parameter uncertainty alone was shown to shift performance estimates for a steel frame [20]. Modelling assumptions matter most at high intensity, where IDA drives the model: discrepancies between experiment and finite-element results were largest under severe shaking [27], column distortion became important at higher loading [28], and the assumed beam-column connection type altered drift response [9]. Two studies limit their conclusions to the single building examined [19], [25].

E. Research Need

Taken together, the reviewed studies show that rankings of brace geometry are tied to context [1]–[4], [10], [14]–[16], [21], [24], that hybrid bracing has been developed mainly through added components or devices [5]–[11], and that, where IDA is used, a building usually carries a single layout [7], [10], [14]–[17]. What remains insufficiently explored is how combinations of brace geometries, and their placement within a

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building, shape interstorey drift and displacement as ground-motion intensity increases, when every arrangement is evaluated under the same building, design and loading conditions. Answering this requires a study in which combinations of conventional brace geometries are applied to one multistorey steel building, designed to a single basis and analysed under one set of ground-motion records using IDA, with interstorey drift ratio, roof displacement and displacement profile compared across intensity levels and the record-to-record uncertainty reported. Such a design would separate the effect of geometry combination and placement from the differences in building layout, design basis and loading that currently confound comparison between published studies. Table IV summarises the gaps and the approach each suggests.

TABLE IV. RESEARCH GAPS AND POSSIBLE APPROACHES

Gap	Evidence	Possible approach
G1. Context-dependent ranking of brace geometry	No two studies share building, basis, record set and measures [1]–[4], [16], [21], [24], [25]	One building, one design basis, equal steel quantity or design base shear, common records
G2. Mixed geometries within one building not examined	Hybrid work combines devices [5]–[9]; geometry varied only by placement [1], [3], [25]	Models combining geometries along the height and in plan, compared with uniform layouts (Fig. 3)
G3. Intensity dependence and limited use of IDA	Rankings change with intensity [17], [19], [24]; IDA models carry one layout [7], [10], [14]–[17]	IDA on every arrangement, with median and fractile curves and collapse capacity
G4. Narrow response measures and little uncertainty reporting	Few studies report confidence intervals [19]; parameter uncertainty matters [20]	Report drift, displacement profile, residual drift and collapse capacity, with bootstrap intervals

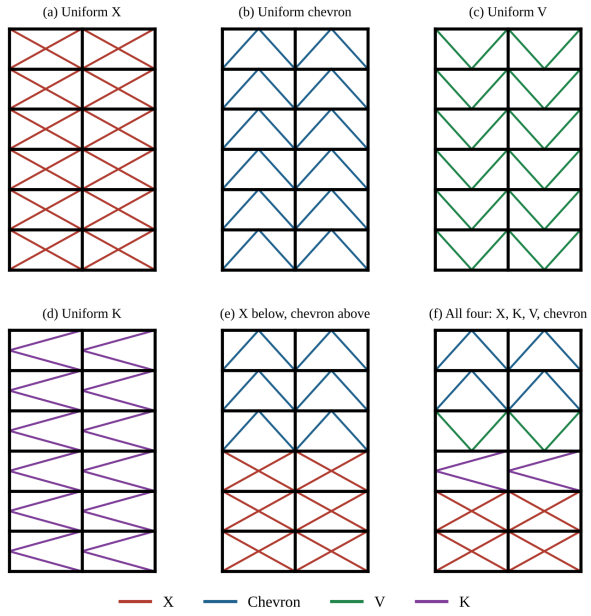


Fig. 3. Illustrative arrangements for a controlled comparison: uniform X, chevron, V and K bracing, X below chevron, and a building combining all four geometries (not results from the reviewed studies).

VIII. IMPLICATIONS FOR FUTURE COMPARATIVE STUDIES

The findings point to six design requirements for studies that compare brace arrangements.

- Use one building, with the same plan, mass and member-design procedure for every arrangement.
- State and hold constant either the steel quantity or the design base shear, so that differences can be attributed to geometry and not to member size [25].
- Use a single ground-motion set, large enough for record-to-record variability to be summarised [12], [13].
- Run IDA and report median and fractile curves and collapse capacity, not only response at one design level [12], [13], [16].
- Report several measures: roof displacement, interstorey drift ratio, displacement profile and, where relevant, residual drift and cost [15], [24].
- Test whether differences between arrangements exceed the scatter, for example by bootstrap confidence intervals [19], and state how far modelling assumptions affect the result [20].

IX. CONCLUSION

This review examined twenty-nine studies on the seismic behaviour of braced steel frames and on incremental dynamic analysis. The studies agree that bracing reduces drift and displacement relative to an unbraced frame and that the arrangement of braces changes steel quantity, cost and the spread of damage. They do not agree on a preferred geometry, because the buildings, design bases, analysis levels and response measures differ together. Hybrid bracing has been developed mainly by combining devices and components, and combinations of conventional geometries within one building have been little examined. IDA has been applied to braced frames, but each building usually carries a single layout, and uncertainty in the comparison is seldom quantified.

Four research gaps follow: the lack of like-for-like comparison of brace geometries, the lack of study of mixed-geometry bracing, the limited use of IDA for comparing arrangements across intensity, and the narrow reporting of response measures and uncertainty. A controlled study that applies uniform and mixed-geometry arrangements to one building, designed to a single basis and analysed by IDA with several response measures, would address them. The conclusions of this review rest on the studies examined, which are not exhaustive, and the numerical values quoted belong to the buildings and conditions of the original work.

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