Influence of Weak Stories on the Seismic Performance of Steel Frame Structures

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Abstract: In steel frame structures, a weak story is a level at which lateral stiffness or shear strength drops relative to adjacent levels, so that inelastic deformation concentrates there under strong ground motion. This paper examines how such a story influences global seismic performance and how the effect can be controlled. The formation of a weak story in steel frames is traced to three sources: an abrupt change in lateral stiffness, an abrupt change in story shear strength, and a non-uniform distribution of gravity load that alters the demand pattern. Their consequences are analysed in terms of inter-story drift concentration, reduction of collapse margin, and the shift of the plastic mechanism from a distributed beam-hinge pattern to a localized column-hinge pattern. Four control measures are compared, namely rocking cores and strongbacks, brace retrofitting, damping wall panels, and connection detailing, and their applicability is discussed against frame height, opening requirements, and construction constraints. The analysis indicates that the influence of a weak story depends less on the magnitude of the stiffness drop than on the degree of drift concentration it produces, and that control measures should be selected by their ability to redistribute drift rather than by their ability to increase local strength.

Keywords: Steel Frame Structure; Weak Story; Inter-Story Drift; Collapse Margin; Seismic Control

1. Introduction

Steel frame structures are widely used in industrial and public buildings where large openings, flexible layouts, and rapid construction are required. Their seismic performance is usually evaluated on the assumption that inelastic deformation spreads over several stories, so that the energy dissipated at each level remains within the capacity of its members. This assumption fails when one story is markedly weaker or more flexible than its neighbours. Under such a condition, the drift demand concentrates at that level, the plastic mechanism localizes, and the collapse capacity of the whole structure falls below the value predicted from a regular configuration.

The weak story problem has received sustained attention because it arises from ordinary design decisions. Ground floors with taller storey height, levels with fewer partitions or infill walls, transfer levels with discontinuous columns, and upper levels with reduced member sections all create the same pattern of abrupt change. In steel frames the situation is aggravated by the sensitivity of member capacity to local buckling, since the plastic rotation capacity of a column or beam section can be exhausted well before the story drift reaches the code limit for collapse prevention [5].

Recent work has addressed the problem from several directions. Aghagholizadeh [1] proposed stepping rocking walls to mitigate weak-story response and redistribute drift in moment-resisting frames. Wu et al. [2] formulated a uniform story drift optimization procedure for seismic design of steel frames, taking drift uniformity as an explicit design objective rather than as a check applied after member sizing. Research on rocking cores [3] and strongback systems [4] showed that inter-story drift concentration can be mitigated by adding an element whose deformation mode differs from that of the frame. Work on collapse assessment [8][9] and on performance-based design targeting collapse fragility [11] provided the quantitative basis for judging how much capacity is lost when drift concentrates.

This paper addresses three questions: how a weak story forms in a steel frame; through

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which response quantities its influence becomes visible; and how the influence can be controlled. The discussion is organized around drift concentration as the intermediate variable that connects the geometric cause to the collapse consequence.

2. Formation Mechanism of Weak Stories

2.1 Stiffness Irregularity and Strength Irregularity

A weak story is commonly identified by two families of indices. The first compares the lateral stiffness of a story with that of adjacent stories, and the second compares its shear strength with the shear demand imposed on it. The two are related but not equivalent. A story can be flexible yet strong, in which case it attracts large drift but yields late, or stiff yet weak, in which case it yields early while drift remains moderate. The response of the structure differs accordingly, and the distinction matters for the choice of control measure.

In steel frames, lateral stiffness at a story is governed by the moment of inertia and the clear height of the columns, by the presence and configuration of braces, and by the degree of restraint provided by beams and connections. A reduction in column section at an upper level, the removal of a brace at one level to accommodate an opening, and an increase in storey height at the ground floor all reduce story stiffness. Shear strength at the same story depends on the plastic moment capacity of the columns, on the brace contribution where braces exist, and on the axial load level, which reduces the available plastic rotation.

2.2 Load Distribution and Demand Pattern

Stiffness and strength irregularity describe the supply side of the problem. The demand side is shaped by how mass and gravity load are distributed over the height. A heavy roof level, a mechanical floor with concentrated equipment, or a change in occupancy that raises live load at one level modifies the inertia force pattern and therefore the story shear profile. When a story with reduced supply coincides with a level of raised demand, the ratio of capacity to demand at that level falls sharply.

The interaction between the two sides is why a weak story cannot be identified reliably from geometry alone. Code-based procedures therefore use drift and strength ratios computed from an elastic or pushover analysis rather than from member dimensions [6]. For steel frames, the practical consequence is that a configuration change introduced late in design, such as the removal of a brace to satisfy an architectural requirement, should be re-evaluated through the same drift and strength ratios rather than judged by inspection.

3. Influence on Seismic Response

The first and most direct consequence of a weak story is drift concentration. Instead of a drift profile that decreases gradually toward the top, the profile exhibits a pronounced kink at the weak level, and the peak inter-story drift ratio at that level can exceed the average by a large multiple. Experimental and numerical studies of steel frames show that once drift concentrates, the local buckling of column sections governs the response, and the deformation capacity of the story is reached earlier than in a regular frame [5][13].

The second consequence is the change of plastic mechanism. A regular frame designed under a strong-column weak-beam philosophy develops beam hinges over several stories. When one story is weak, hinges form at the column ends of that story instead, and the mechanism becomes a single-story sway mechanism. This shift reduces the number of yielding members that share the dissipated energy and increases the rotation demand on each of them. Modelling studies of frames with drift concentration report that the collapse mechanism assumed in design is no longer the mechanism that actually forms [7][11].

The third consequence is the reduction of collapse margin. Collapse margin ratio is defined as the ratio between the ground motion intensity causing collapse and the intensity of the design-level motion, and acceptable values depend on the confidence level required [8]. Work on steel frames with concentric braces [9] and on performance-based design targeting collapse fragility [11] indicates that drift concentration lowers this ratio, because the local deformation capacity at the weak story is exhausted while the rest of the structure still has reserve. The reduction is not proportional to the stiffness drop; a moderate irregularity at a level that already carries high demand can reduce the margin more than a larger irregularity at a level with low demand.

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Table 1. Response Quantities for Detecting Weak-Story Influence

Quantity	Definition	What it detects	Limitation
Peak inter-story drift ratio	Maximum story drift divided by story height	Location and severity of drift concentration	Does not indicate whether yielding is local or global
Drift concentration factor	Ratio of peak story drift to average story drift	Degree of localization independent of intensity	Requires a reference regular model
Story stiffness ratio	Ratio of story stiffness to that of adjacent stories	Geometric source of irregularity	Does not reflect strength or demand
Story shear strength ratio	Ratio of story strength to design story shear	Strength irregularity under the actual demand pattern	Depends on the analysis method used
Collapse margin ratio	Ratio of collapse intensity to design intensity	Reserve against collapse	Requires incremental dynamic analysis

4. Parametric Analysis Framework

A parametric framework is needed because the influence of a weak story depends on the joint effect of several variables rather than on any single one. The variables are the position of the weak story along the height, the ratio of its stiffness to that of adjacent stories, the ratio of its strength to the corresponding demand, and the axial load level in its columns. Each variable is varied while the others are held at their reference values, and the response quantities listed in Table 1 are recorded.

Position matters because the story shear profile and the modal contribution differ along the height. A weak story at the base intercepts the full base shear and usually produces the largest drift concentration. A weak story at mid-height interacts with higher mode effects, so the drift concentration is smaller at the same stiffness ratio but the acceleration demand at upper levels increases. A weak story near the top produces limited drift concentration but can raise the whipping response at the roof.

Stiffness ratio and strength ratio act together. When the stiffness ratio is low but the strength ratio remains adequate, the structure develops large drift at the weak level while remaining elastic elsewhere, and the controlling limit is usually the drift limit for the occupancy or life-safety performance level. When both ratios are low, yielding localizes and the controlling limit becomes deformation capacity. The distinction determines whether a stiffness-based or a strength-based control measure is appropriate, and it is the reason why control measures should be selected against the governing limit state rather than against the irregularity alone.

A fourth variable, the axial load level in the columns of the weak story, acts on capacity rather than on demand and therefore deserves separate treatment. As axial load rises, the plastic rotation available in a steel section falls and the onset of local buckling moves to a smaller drift. The same stiffness ratio therefore produces a larger loss of collapse margin when the weak story carries a high axial load, which is the usual situation at the base of a frame and at levels below a setback. Residual drift is governed by the same interaction, since a story that has buckled locally recovers little of its deformation after the motion ends [13]. For this reason the axial load level should be recorded alongside the stiffness and strength ratios in any parametric study of weak-story influence.

5. Control Measures

Four families of control measures are available for steel frames, and they act through different mechanisms.

Table 2. Comparison of Control Measures for Weak Stories in Steel Frames

Measure	Mechanism	Applicable condition	Main limitation
Rocking core or strongback	Imposes a near-uniform drift mode over the height	Frames where an additional vertical element can be accommodated	Requires a stiff foundation and increases base demand
Brace retrofitting	Raises story stiffness and strength directly	Stories where openings permit brace placement	Transfers demand to adjacent stories and connections
Damping wall panels	Adds distributed energy dissipation without large stiffness	Frames with semi-rigid connections and infill walls	Performance depends on connection detailing and panel durability

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	gain		
Connection detailing	Raises local deformation capacity at the weak level	Cases where geometric irregularity cannot be removed	Does not reduce drift demand, only raises tolerance

Rocking cores and strongbacks address drift concentration directly. Qu et al. [3] showed that implementing rocking cores in multi-story concentrically braced steel frames mitigates drift concentration by imposing a deformation mode that the frame alone cannot develop. Lin et al. [4] examined stiffness configuration of strongbacks and found that the mitigating effect depends on how the strongback stiffness is distributed rather than on its total value. Aghagholizadeh [1] obtained drift redistribution in moment-resisting frames using stepping rocking walls, which act on the same principle while allowing the rocking element to be placed outside the frame line.

Brace retrofitting raises both stiffness and strength at the weak level. Das and Deb [12] evaluated a steel braced frame retrofitted with self-centering buckling-restrained braces and reported improved performance together with reduced residual drift. Zahrai and Mousavi [10] used a cable-pulley brace arrangement to improve story drift distribution in moment-resisting frames with large openings, which is the configuration where conventional diagonal braces cannot be placed. The limitation of brace retrofitting is that it shifts demand to adjacent stories and to the connections, so the retrofitted level has to be checked together with its neighbours.

Damping wall panels act mainly through energy dissipation. Zhang et al. [7] reported an experimental and numerical study of a semi-rigid steel frame infilled with prefabricated damping wall panels, in which the panels contributed dissipation while the stiffness increase remained moderate. This behaviour is useful when the weak story is stiff enough to satisfy drift limits but lacks dissipation capacity.

Connection detailing is the measure of last resort, applied when the geometric irregularity cannot be removed. Zhang et al. [14] examined anti-progressive collapse performance of fully bolted steel frame connections and showed that connection configuration affects the reserve capacity of the frame after local failure. Dowden and Baker [6] reported that rocking beam-to-column connections combined with buckling-restrained brace fuses allow the frame to sustain drift without connection fracture. The measure raises the drift the structure can tolerate rather than the drift it demands, and it should be combined with one of the other three where possible.

6. Discussion and Conclusion

The argument developed in this paper is that the influence of a weak story in a steel frame is mediated by drift concentration. An irregularity in stiffness or strength becomes consequential only to the extent that it localizes inelastic deformation, and the severity of the consequence is measured by the collapse margin rather than by the irregularity ratio itself. This view has a practical implication for design review: a configuration change should be assessed by its effect on the drift profile and on the collapse margin, and not by whether it keeps the stiffness ratio within a prescribed bound.

The discussion so far applies to both new design and the assessment of existing buildings, but the two contexts differ in what can be changed. In a new design the irregularity can usually be removed before the member sizes are fixed, so the choice lies between redistributing drift and avoiding the concentration altogether, and the second is preferable because it leaves no residual irregularity to be checked. In an existing building the choice is limited to what the occupation and the existing structure permit, which usually means adding an element or a device rather than changing the layout. The verification step matters more in the second context, because the as-built stiffness distribution is known only through the assessment itself and the treatment is selected against an estimate of it.

The choice among control measures follows from the same reasoning. Measures that redistribute drift, such as rocking cores, strongbacks, and cable-pulley braces, act on the cause. Measures that add dissipation, such as damping wall panels, act on the demand. Measures that raise local deformation capacity, such as connection detailing, act on the tolerance. Where the irregularity cannot be removed, combining a drift-redistribution measure with a capacity measure usually gives a better result than strengthening the weak story alone, because the latter leaves the drift concentration in place and transfers it elsewhere.

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Three limitations should be acknowledged. The discussion is based on the mechanisms reported in the cited experimental and numerical studies rather than on a new parametric data set, so the relative weight of each variable has not been quantified for a specific frame. The comparison of control measures is qualitative in respect of cost and constructability, and a selection for a particular project would need both. The effect of masonry infill walls, which are present in many steel frames and alter story stiffness substantially, is not treated here.

Further work can proceed in three directions: building a parametric data set for steel frames with a single weak story and quantifying the sensitivity of collapse margin to position, stiffness ratio, and strength ratio; testing the combination of a rocking element with damping panels on the same frame; and examining how infill walls change the identification of the weak story in practical designs.

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