Identification Method and Treatment Measures for Weak Stories in Concrete Frame Structures

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Abstract: A weak story in a concrete frame structure is a level whose lateral stiffness or shear strength is markedly lower than that of adjacent levels, with the result that inelastic deformation concentrates there under strong ground motion. This paper examines how such a story is identified and how it is treated. The formation of weak stories is traced to vertical irregularity in stiffness, irregularity in strength, and the interaction between the two and the story shear demand. Code-based identification criteria are compared, and it is shown that criteria expressed as stiffness ratios and criteria expressed as strength ratios do not always identify the same story, because a story can be flexible yet strong or stiff yet weak. Four identification procedures are then compared, ranging from elastic drift ratios to incremental dynamic analysis, and their resolution and cost are set against each other. Five treatment measures are discussed, including member enlargement, addition of shear walls or braces, installation of damper braces, partial infilling, and base isolation, and the conditions under which each is appropriate are stated. The paper argues that identification and treatment should be linked through the governing limit state, and that the effectiveness of a treatment measure should be verified by the drift profile it produces rather than by the strength it adds.

Keywords: Concrete Frame Structure; Weak Story Identification; Vertical Irregularity; Story Drift Ratio; Seismic Strengthening

1. Introduction

Concrete frame structures account for a large share of the building stock in Chinese cities, and a substantial part of that stock was designed before the current code provisions on vertical irregularity were fully applied. Among the various forms of irregularity, the weak story is the one most often associated with severe earthquake damage, because it converts a structure intended to dissipate energy over several levels into one that dissipates it at a single level.

The identification of a weak story is not straightforward. Its definition refers to a comparison between one story and its neighbours, and the comparison can be made on stiffness, on strength, or on the deformation that results when the two are set against the demand. These three comparisons do not always point to the same story. A level with a taller storey height is flexible but may still carry an adequate margin against its shear demand, while a level with a reduced column section may satisfy the stiffness ratio yet yield early. Empirical studies of soft-storey irregularity in reinforced concrete buildings report that the severity of the consequence depends on which of the two irregularities governs [1][7].

Treatment adds a second layer of difficulty, because a measure that raises the strength of the weak story also raises its stiffness and therefore changes the distribution of demand over the whole height. Strengthening the wrong level, or strengthening the right level in the wrong way, can move the concentration elsewhere. Experimental and analytical studies of strengthening strategies for reinforced concrete frames have shown that the improvement in seismic resilience depends on how the measure changes the deformation pattern rather than only on the capacity it adds [9][10].

This paper addresses two questions in sequence: how a weak story in a concrete frame should be identified, and how the identified weakness should be treated. The discussion is aimed at the assessment of existing buildings as well as at the review of new designs in which an architectural requirement introduces irregularity late in the process.

2. Formation and Classification

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2.1 Stiffness Irregularity and Strength Irregularity

A weak story arises when the supply of stiffness or strength at one level falls relative to the demand placed on it. The causes are well known and largely architectural. An open ground storey used for parking or retail removes the infill walls present at upper levels, so the stiffness of that storey drops while its shear demand, being at the base, is the largest in the structure. A transfer storey with discontinuous columns or walls produces a similar pattern. A setback in the upper part of a building reduces both mass and stiffness, but not necessarily in the same proportion.

The two irregularities should be kept apart because they lead to different behaviour, and because a classification based on one of them has to be read together with the other. A stiffness-based classification identifies the level at which drift will concentrate, which is the level whose non-structural elements, partitions, and equipment will be damaged first. A strength-based classification identifies the level at which yielding will begin, which is the level whose members govern the collapse capacity. The two levels are frequently the same in practice, because the architectural decisions that remove stiffness also remove the wall contribution to strength, but the cases where they differ are the cases in which a treatment selected from one classification alone fails to address the governing problem [1]. Stiffness irregularity produces drift concentration, and its consequence appears first at serviceability and life-safety limit states. Strength irregularity produces early yielding and a localized plastic mechanism, and its consequence appears at the collapse limit state. A story with both irregularities produces drift concentration and early yielding together, which is the combination associated with the poorest performance.

The design intent expressed in the strong-column weak-beam philosophy is relevant here, because it determines whether the yielding that does occur is distributed or localized. The capacity design procedures that underpin this philosophy were developed precisely to keep the mechanism distributed and to prevent the formation of a single-story sway mechanism [14]. Work on beam-column joints designed under that philosophy shows that the joint behaviour governs whether the intended mechanism is achieved, and that an irregularity which adds strength at some bays changes the sequence in which hinges form [11].

2.2 Code-Based Identification Criteria

Design codes express the identification of a soft or weak story through ratios computed from an analysis rather than through geometry. The common forms are a ratio comparing the lateral stiffness of a story with that of the story above or with the average of the stories above, and a ratio comparing the shear strength of a story with the shear demand obtained from the analysis. Comparative assessment of code-based criteria for vertical stiffness irregularities has shown that the criteria used in different codes do not identify the same set of buildings as irregular, and that the disagreement is largest for buildings with moderate irregularity [6].

Demirtas et al. [2] investigated code-based criteria for soft-story irregularity and reported that the thresholds used in different provisions lead to different classifications, which matters because the classification determines whether a detailing requirement applies. The practical consequence is that a building classified as regular under one criterion may be irregular under another, and an assessment should state which criterion was applied. A further difficulty is that the stiffness ratio is usually evaluated on an elastic model, while the behaviour of interest is inelastic, so the ratio indicates a potential for concentration rather than the concentration itself.

3. Identification Procedures

Four procedures are available, and they differ in what they resolve and in what they cost.

Table 1. Comparison of Identification Procedures

Procedure	Basis	What it resolves	Cost and limitation
Elastic story drift ratio	Linear elastic analysis under design lateral force	Locates levels where drift exceeds the code limit	Does not represent redistribution after yielding
Story stiffness and strength ratio	Comparison of story properties with adjacent stories	Identifies the geometric and strength source	Depends on the criterion and threshold adopted
Pushover analysis	Nonlinear static analysis	Shows the hinge sequence	Result depends on the

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	under a monotonically increasing lateral pattern	and the mechanism that forms	assumed load pattern
Incremental dynamic analysis	Nonlinear time-history analysis scaled to increasing intensity	Quantifies collapse margin and its uncertainty	High computational cost and record-to-record variability

The elastic story drift ratio is the least expensive and is the form used in most routine design checks. Its limitation is that it describes the structure before redistribution, so it can identify a level as critical that in fact sheds demand once yielding spreads, or miss a level that becomes critical only after redistribution.

The stiffness and strength ratio procedures are the forms adopted in code provisions, and their limitation is the dependence on the threshold. Because the criteria differ between codes [2][6], the same building can be classified differently, and the assessment should therefore report the criterion used together with the ratio obtained.

Pushover analysis resolves the hinge sequence and the mechanism, which is what the code criteria approximate. Aydiner and Sevim [3] investigated soft story irregularity in reinforced concrete structures through pushover analysis from two-dimensional frames to three-dimensional buildings, and showed that the two-dimensional idealization changes the identification, because torsional effects and the contribution of transverse frames are absent from it. This is a caution against identifying the weak story from a single plane frame in a building with an irregular plan.

Incremental dynamic analysis gives the collapse margin and its dispersion, and it is the only procedure that answers the question of how much reserve remains once concentration occurs. Its output is usually expressed as a collapse margin ratio, and acceptable values of that ratio depend on the confidence level required [13]. Studies of non-ductile open ground story frames [8] and of the seismic response of soft-story reinforced concrete frames [7] both report that the collapse mechanism assumed in design is not the mechanism that forms, which is precisely what this procedure is able to detect.

4. Treatment Measures

Five measures are in common use, and they act on different parts of the problem.

Table 2. Treatment Measures for Weak Stories in Concrete Frames

Measure	Mechanism	Applicable condition	Main limitation
Member enlargement by jacketing or section increase	Raises local strength and stiffness	Localized weakness in a small number of members	Adds stiffness and shifts demand to adjacent levels
Addition of shear walls or steel braces	Raises story stiffness and provides an alternative load path	Stories where walls or braces can be accommodated	Requires foundation check and changes architectural layout
Installation of hysteretic damper braces	Adds dissipation without a large stiffness gain	Cases where drift demand governs rather than strength	Devices require inspection and replacement planning
Partial infilling with reinforced concrete walls	Removes the stiffness irregularity at the open story	Open ground stories with sufficient remaining space	Reduces usable floor area and adds mass
Base isolation or added damping at the base	Reduces the demand transmitted to the superstructure	Buildings where isolation can be inserted at the base	High cost and requires a separation gap and detailed check

Member enlargement is the most direct response to a strength irregularity and is widely applied when the weakness is confined to a few columns. Its limitation is that it raises stiffness as well, so the enlarged members attract more force and the neighbouring members must be rechecked.

Adding shear walls or braces raises both stiffness and strength and provides a second load path. Rahimi and Maheri [10] studied the effects of steel X-brace retrofitting of reinforced concrete frames on the seismic performance of frames and their elements, and reported that the benefit depends on how the added elements interact with the existing members rather than on their capacity alone.

Damper braces address the case where the drift

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demand governs rather than the strength. Izadpanah et al. [4] examined retrofitting of stepped gravity load designed reinforced concrete buildings with soft-story irregularity by installing hysteretic damper braces, which add dissipation while keeping the stiffness increase moderate. This is the appropriate choice when the story is flexible but not weak in strength, because enlarging members would add stiffness the structure does not need.

Partial infilling removes the cause at an open ground storey. Mallikarjuna et al. [5] carried out an experimental study on the seismic retrofitting of an existing non-ductile open-ground story reinforced concrete frame by partial infilling with reinforced concrete shear walls, and showed that the measure restores a more uniform stiffness profile. The cost is the loss of usable area, which is often the reason the storey was open in the first place.

Base measures reduce the demand rather than raise the capacity. They are the most expensive option and are usually reserved for buildings where the superstructure cannot be modified. Where the irregularity is combined with a weak or soft soil condition, or where the building must remain in use during works, the choice among measures should be made against the disruption each causes as well as against its mechanical effect [9][12].

5. Application Procedure

A five-step procedure follows from the preceding discussion. The first step is to establish the as-built geometry and material condition, because the identification depends on the actual stiffness distribution rather than on the design drawings. The second step is to compute the stiffness and strength ratios under a stated criterion and to record the criterion used, since the classification depends on it [2][6]. The third step is to run a pushover analysis on a three-dimensional model and to observe where hinges form and in what order, rather than to rely on the drift ratio from a plane frame [3]. The fourth step is to select a treatment measure against the governing limit state: a strength-based measure when the hinge sequence shows a localized mechanism, a stiffness-based measure when the drift profile shows concentration without early yielding, and a dissipation-based measure when the drift demand governs. The fifth step is to verify the treated structure by recomputing the drift profile and, where the decision is significant, the collapse margin [13], and to confirm that the concentration has been reduced rather than moved.

Two conditions govern whether the procedure can be carried out as stated. The first is the quality of the input data, because the stiffness distribution of an existing building depends on the as-built member dimensions, the concrete strength actually achieved, and the presence and condition of infill walls, none of which is reliably available from drawings alone. Where material testing and a survey of the wall layout are not possible, the identification should be reported as conditional on the assumed values, and the treatment should be selected so that it remains effective across the plausible range. The second condition is the acceptable level of disruption, since measures that add walls or braces at an open storey change the use of the building, and this constraint frequently decides between a mechanically preferable measure and the one that is adopted [9][12].

The fifth step is the one most often omitted, and it is the one that prevents the failure mode in which strengthening a story transfers the concentration to the story above. Verifying by drift profile rather than by member capacity is what distinguishes a treatment that works from one that appears to work in the member checks.

6. Discussion and Conclusion

The identification and the treatment of a weak story in a concrete frame should be linked through the governing limit state. Identification criteria based on stiffness ratios detect a potential for drift concentration, and those based on strength ratios detect a potential for early yielding. The two do not always identify the same story, and the assessment should therefore state which was applied and why. Treatment then follows from the mechanism observed: measures that add stiffness for concentration without yielding, measures that add strength for a localized mechanism, and measures that add dissipation when drift demand governs.

Two cautions follow. The first is that treatment changes the demand distribution, so the verification has to cover the whole structure and not only the treated level. The second is that the classification of a building as regular or irregular depends on the criterion adopted, and the criteria in different provisions disagree most for buildings with moderate irregularity, which is the range where most practical decisions are

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made.

Three limitations should be acknowledged. The comparison of identification procedures is based on their published applications rather than on a common benchmark building, so their relative resolution has not been measured under identical conditions. The treatment measures are compared on their mechanical effect, and cost, disruption, and constructability are mentioned only qualitatively. The effect of masonry infill walls, which strongly influences story stiffness in concrete frames and is often the origin of the irregularity, is treated here only through the partial infilling measure.

Further work can proceed in three directions: application of the five-step procedure to a set of existing buildings with open ground stories and comparison of the identification obtained from each procedure; parametric study of how far a stiffness-based treatment can be applied before the concentration moves to the story above; and joint treatment of infill distribution and weak-story identification, since the two are usually the same problem seen from different sides.

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