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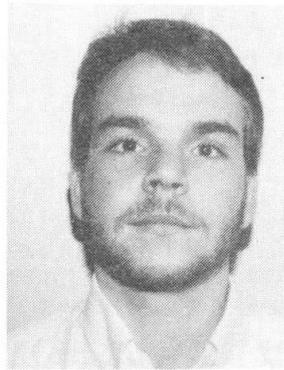
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Retrofitting of Reinforced Concrete Structures with Steel Bracing Systems

Restauration de structures en béton armé avec des contreventements métalliques

Verstärkung von Stahlbetonbauten mit Stahlverbänden

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SUMMARY

Steel bracing systems have been used for the retrofitting of reinforced concrete buildings with seismically inadequate lateral resistance. Applications of this retrofitting technique are presented and the main aspects of the design of the bracing system are discussed. The behavior under inelastic cyclic lateral deformations of a steel braced frame with weak columns is investigated with an analytical model.

RÉSUMÉ

Certaines structures en béton armé ayant présenté une mauvaise résistance latérale aux séismes ont été restaurées au moyen de contreventements métalliques. Trois applications pratiques de cette technique sont présentées et les principaux aspects du calcul du système de contreventement sont discutés. Le comportement d'un cadre contreventé soumis à des déformations latérales inélastiques est étudié à l'aide d'un modèle analytique.

ZUSAMMENFASSUNG

Für die Verstärkung von Stahlbetonbauten mit ungenügendem Horizontalwiderstand gegen Erdbebeneinwirkungen können Stahlverbände verwendet werden. Drei praktische Anwendungen dieser Technik werden vorgestellt und die prinzipiellen Aspekte der Bemessung solcher Verbände werden besprochen. Anhand eines analytischen Modells wird das Verhalten eines mit Stahlstreben verstärkten Rahmens unter nicht elastischen, zyklischen Verformungen untersucht.



1. INTRODUCTION

A large number of existing reinforced concrete frame structures are in need of seismic retrofitting because of inadequate lateral resistance. The inadequacy typically results from a poor design, a change in usage, or a change in design loads subsequent to the original construction. One promising retrofitting scheme uses diagonal steel bracing to strengthen and stiffen the structure. The bracing system is typically attached to the perimeter frames. By working on the exterior of the building, disruptions are minimized during and after construction.

2. APPLICATIONS

Steel bracing has been used for retrofitting inadequate structures as well as for repairing damaged structures. A well-publicized example is the five story Japanese school building shown in Fig. 1 [1]. The perimeter frames consist of deep spandrel beams and short columns damaged in the 1978 Tokachi-Oki earthquake. The damaged frames were retrofitted with a bracing system detailed to provide maximum energy dissipation under cyclic inelastic loading. Retrofitting also included altering the deep spandrel beams in order to transform the brittle "weak column-strong beam" frame into a ductile "strong column-weak beam" frame.

Fig. 2 shows a twelve story medical building in Mexico City, which suffered structural damage to column and beams of the first three stories during the 1979 Petatlan earthquake and was subsequently repaired and strengthened with external steel trusses [2]. The trusses feature steel columns to resist high overturning moments. The slabs were strengthened to transmit the seismic shear forces to the new bracing system. The foundations of the perimeter frames were strengthened with steel piles. The project was completed in ten months at approximately 20 percent of the replacement cost of the building and with minimal disturbance to the users. Unlike many surrounding buildings, the retrofitted structure performed very well in the devastating 1985 earthquake.

The building of Fig. 4, the Zaragoza Hospital in Mexico City, suffered only minor damage in the 1985 earthquake. To reduce the possibility of damage in future events, diagonally braced rectangular steel frames are being added in the bays of the perimeter frames. The prefabricated steel bracing units are positioned and concrete is cast between the steel bracing unit and the existing concrete frame. Shear is transferred by dowels welded to the bracing unit and epoxy grouted into the concrete frame. The braces are square built-up sections designed to yield rather than buckle in compression.

The use of the bracing retrofit technique has also been considered in the U.S., particularly for cases similar to the Sendai School, which is typical of many buildings constructed in the 1950's in seismic zones. The behavior of a frame featuring weak short columns and strong beams retrofitted with a steel bracing system was investigated experimentally using a large scale model shown in Fig. 3 [3]. The experimental work was coupled with the analytical study presented in the next section.

3. ANALYTICAL STUDY OF A STEEL BRACED FRAME

3.1 Model

To further understanding seismic behavior of a steel braced frame, the lateral load-drift relationship under cyclic loading of a simple model was analyzed.



Fig. 1 Sendai School, Japan [1]

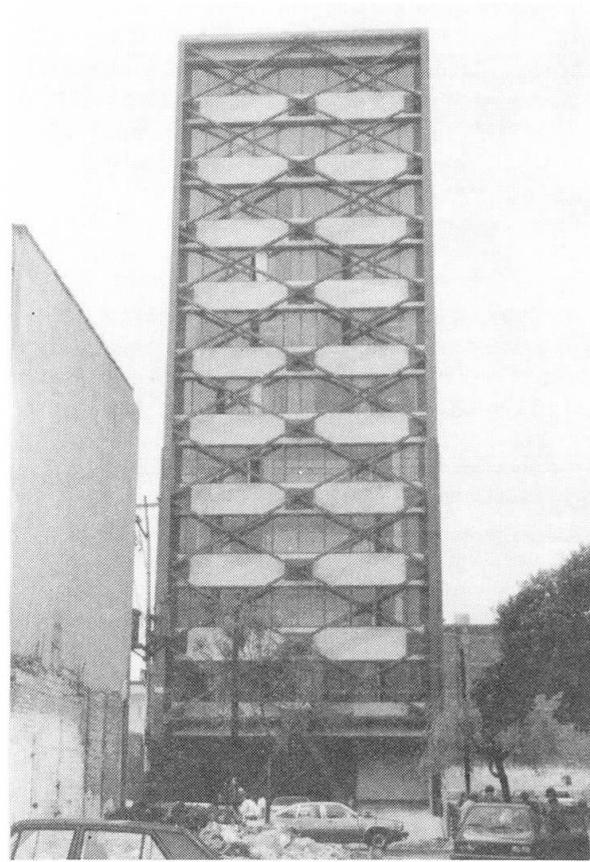
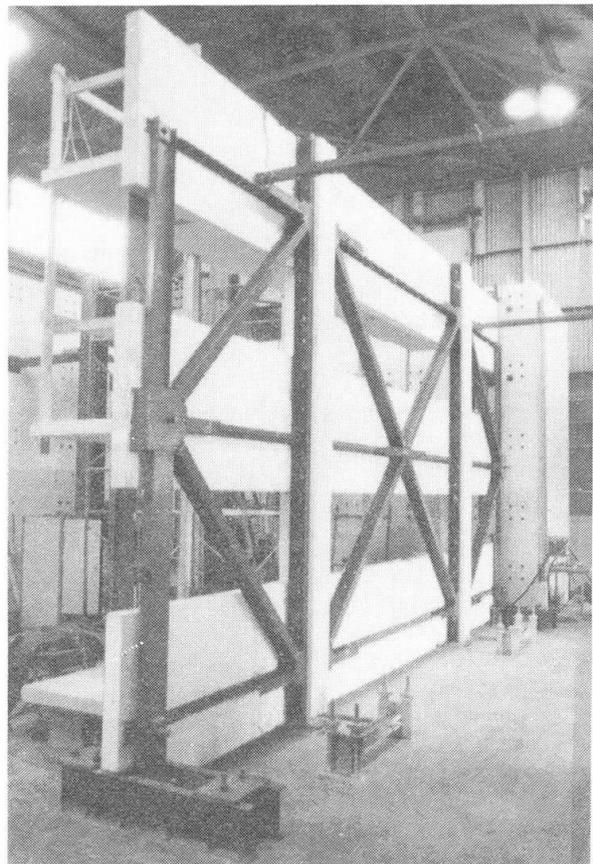
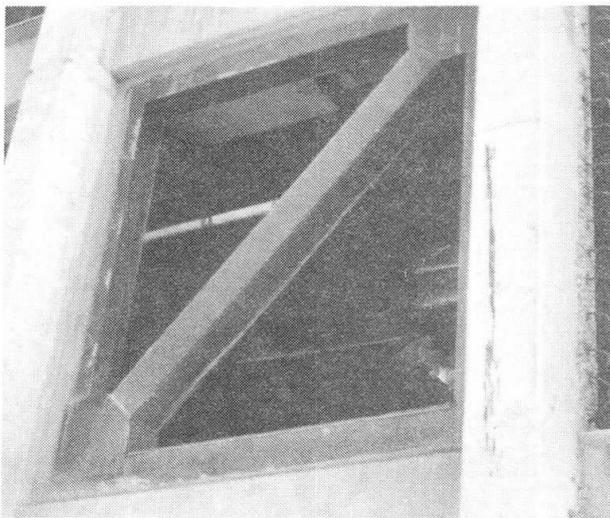


Fig. 2 Durango 49 Building,
Mexico City [2,4]

Fig. 3 Experimental test of
a steel braced frame [3]

Fig. 4 Zaragoza Hospital, Mex. C. [4]





The analytical model features two beams and a column simulating the frame of Fig. 5 braced as shown in the sketch in Fig. 6. The support conditions were chosen to reproduce boundary conditions of an interior column of the braced frame under lateral loading. The analytical models for the hysteretic behavior of the columns, beams, and braces were based on experimental results [5,6]. The computer program was checked using data from the experimental braced frame test.

3.2 Computed Response

In the analytical study, the slenderness ratio (kl/r) and the strength was varied and the model was analyzed for various cyclic loadings [4]. In the case described here, the braces have a slenderness of 80 and were designed to double the strength of the structure. The model was subjected to a single cycle of loading with reversal at large inelastic drift. The contribution of the frame and braces to the lateral resistance of the braced frame is shown in Fig. 5. The failure sequence is shown in Fig. 6. Important points in the response are numbered. First, the columns (1) and then the beams (3) crack. The bracing system remains elastic until the compression brace B2 buckles (4) at a drift of 0.20 percent and at 85 percent of the peak strength. The columns fail in shear (5) at a drift of 0.40 percent, the braced frame then loses strength until point 7, when the column has no lateral capacity in either loading direction. From point 7 onward, the frame no longer contributes to the lateral resistance and the bracing system controls behavior. Following the loading reversal (8), brace B1 is loaded in compression, buckles at point 9, and reaches post-buckling capacity (11) before brace B2 yields (12). When the load is reversed (13), brace B2 buckles for the second time when it reaches the post-buckling load level (14), and brace B1 yields (16) at a large drift level. The large reduction of strength and stiffness between first and

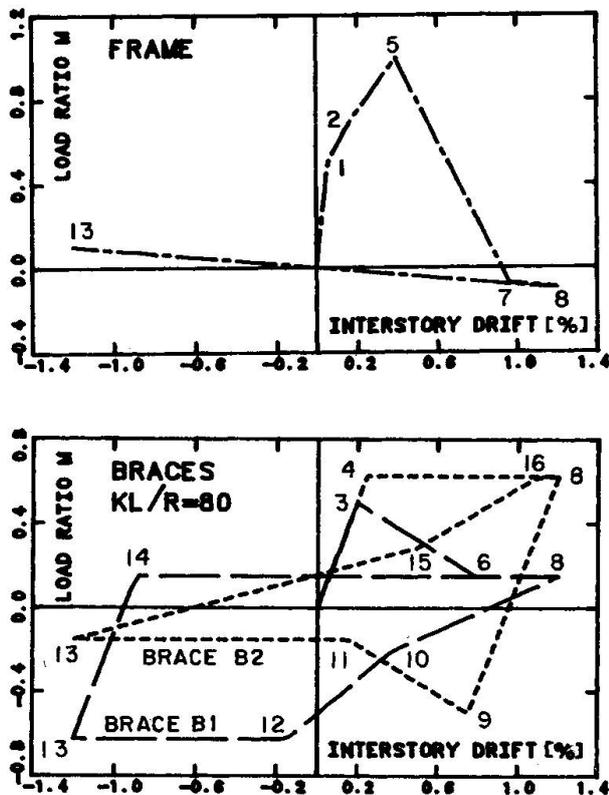


Fig. 5 Frame and bracing system under cyclic loading [4]

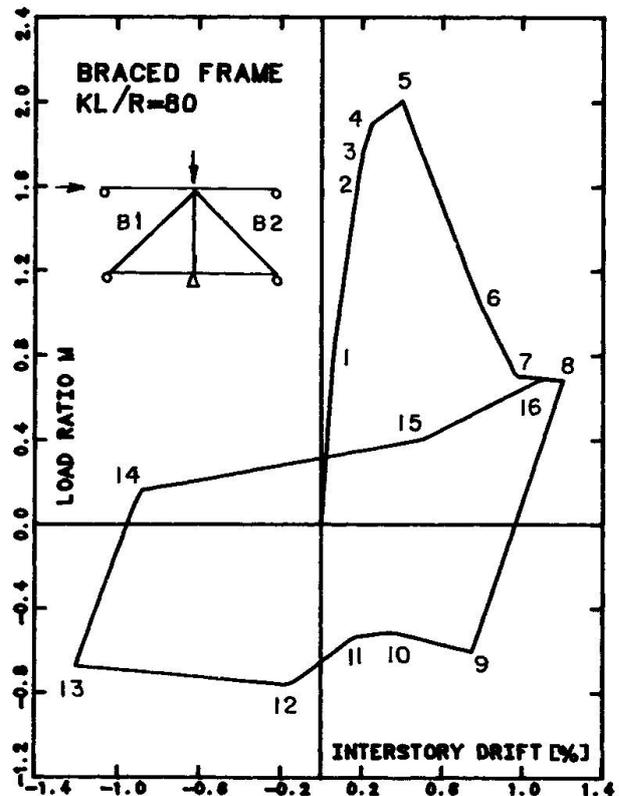


Fig. 6 Braced frame under cyclic loading [4]



second loading in the initial direction is due to loss of short column capacity and to buckling of the braces.

3.3 Behavior

Inelastic buckling of the braces is the main problem in designing a steel braced system. As was observed in experimental tests [3], the alternate buckling and yielding of the brace is linked with large local deformations at the brace connections which may lead to failure. Buckling also limits energy dissipation in the bracing system. One way to avoid inelastic buckling is to use very low slenderness ratios to guarantee that the braces yield rather than buckle in compression. Another way to prevent inelastic buckling is to use braces which buckle elastically, such as cables. The cables could be prestressed to improve the serviceability behavior. Alternatively, the bracing system may be designed to remain elastic which, in addition to preventing buckling, has the advantage of limiting drift during an earthquake. The steel bracing scheme is actually very well-suited for elastic design, since most of the added strength is in the elastic range for reasonable brace slenderness ($kl/r < 80$). The performance of the braced frame is optimized if the bracing system and the frame are well-matched in terms of their relative deformability. In Fig. 5 the two systems are well-matched, since the columns do not suffer substantial damage before they reach peak elastic strength.

4. THE RETROFITTING PROCESS

4.1 Decision to Brace a Structure

The main steps in the process leading to retrofitting a structure with a steel bracing scheme are outlined in the flowchart of Fig. 7. The evaluation of the seismic adequacy of the structure (step 1) consists of comparing performance requirements with expected behavior under seismic loads. If the structure is found inadequate (step 2), the owner must choose between retrofitting or replacement (step 3). The retrofitting scheme must be designed to correct deficiencies in the existing structure; that is, lack of strength, stiffness, or ductility (step 4). The retrofitting scheme should also be considered in terms of its impact on aesthetic qualities and on the usability of the building during and after construction. The rest of the flowchart is for the case where a steel bracing scheme best satisfies the requirements defined in step 4. Bracing may be combined with other retrofitting techniques. For example, bracing of perimeter frames may be used with column strengthening or infill shear walls in interior frames.

4.2 Design of the Bracing System

The choice of the bracing system configuration (step 6) includes selecting frames and bays to be braced and selecting bracing patterns.

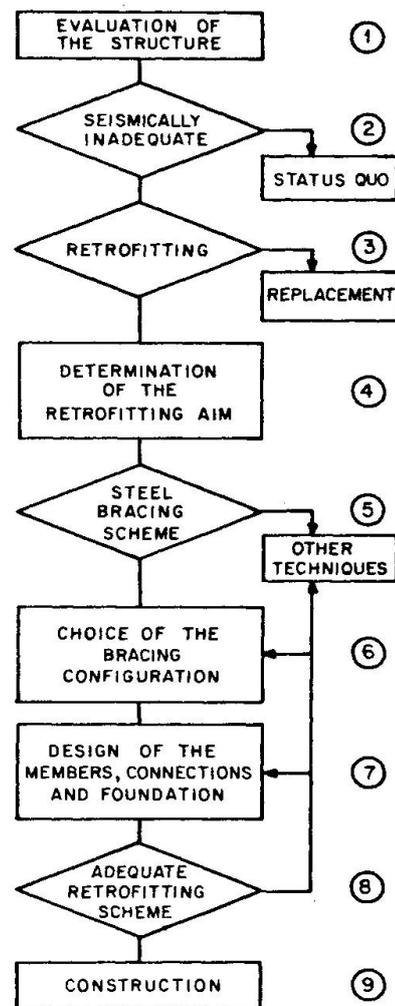


Fig. 7 Flowchart for the retrofitting process [4]



Changes in the force distribution in the existing structure must be considered to avoid overloading certain members, or introducing torsional eccentricities in the plan of the structure, or within the braced frames. Once a configuration has been chosen, the bracing system can be designed and detailed (step 7). To maximize the drift range in which the braced frame responds elastically, brace slenderness should be low and drift levels at which the frame and the bracing system suffer significant damage should be kept as similar as possible. If columns function as vertical elements of the bracing system, they must be able to carry the additional loads. Connections of the bracing system must be detailed (welds, bolted joints) carefully to avoid local failures under inelastic cyclic deformations. The foundations of the braced frames may need strengthening because the retrofitted structure typically imposes greater forces on foundations. In the construction phase of a retrofitting scheme (step 8), allowance should be made for higher fitting tolerances and for in-situ modifications.

6. CONCLUSION

Steel bracing systems are very well-suited for retrofitting operations aimed toward strengthening and/or stiffening reinforced concrete structures with inadequate lateral resistance. The main advantage of the technique is that strength and stiffness can be adjusted to achieve a variety of design objectives because the bracing system is independent of the existing frame. The retrofitted structure can be designed to respond primarily in the elastic range, thereby limiting damage which would occur under drift in the inelastic range. Problems associated with inelastic buckling may be alleviated by using braces which buckle elastically, such as cables.

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