THE PERFORMANCE OF STAIRWAYS IN EARTHQUAKES

Catherine Roha (I)

SUMMARY

Stairways are essential building components serving critical functions of emergency access and egress following earthquakes and fires. Stairways also may significantly affect the seismic response of structural systems. Past earthquakes have exposed a wide variety of problems and failures related to stairway/structure interactions. Present architectural and structural engineering practices may not address these interactions adequately. A model code for seismic resistant design and construction of stairways is proposed. Directions for future research and recommendations for mitigation measures are outlined.

INTRODUCTION

Stairways play significant roles in building performance during earthquakes due to dynamic interactions with primary structural systems and the occurrence of unanticipated and undesirable responses. Damaged stairways adversely affect evacuation and rescue, fire fighting, salvage, and restoration. Severe earthquakes may require that building occupants rescue themselves, elevators may not be functional, and imminent secondary hazards such as fire or flooding may make immediate evacuation imperative.

Stairways are permanent, rigid, and frequently heavy elements often extending the full height of the building, connected directly or indirectly to the primary structure. In multi-story fire-resistive buildings, stairs are typically constructed of reinforced concrete, steel, or a combination of those materials. The stairway system includes stair flights and landings, enclosure walls, doors and windows, lighting, ventilating systems, standpipes, and other services. Stairways may be open monumental staircases, enclosed fire stairs, exterior fire escapes, or service stairs.

The main objective of this paper is to raise the issue of stairway interactions and hazards, summarizing studies conducted by the author and discussed in detail in Reference 1. This initiation study of stairway performance was based on discussions with architects and engineers practicing in the San Francisco area, and on extensive review of earthquake reconnaissance reports, engineering studies, handbooks, reference materials, and building codes. The report established groundwork for further investigations and analytical studies.

(I) Architect, Berkeley, California, USA

PAST PERFORMANCE

Although many stairways in multi-story buildings have withstood strong seismic shaking satisfactorily, other stairways have exhibited a wide range of significant damage. The most critical life safety issues are interference of stairway structural behavior with the building's overall seismic response which results in collapse, and interference of damage with emergency exiting and rescue. The typical diagonal brace-like configuration of stairways can, at one extreme, increase the overall lateral stiffness of the structure and significantly alter the dynamic character of the structure as a whole, or, at the other extreme, simply modify local response behavior of the structural element to which it is attached. The change in overall lateral and torsional stiffness often results in higher seismic force levels than would be anticipated by considering the primary structure alone and, in some cases, has jeopardized the stability of the whole structure. Damage to stairways can also result.

Stairway landings connected to columns at mid-height have added unexpected stiffness and created "short columns," resulting in brittle shear failures (Fig. 1). "Short beams" have been created by stair flight connections. High local shear stresses have occurred in floor diaphragms due to restraint by stair enclosure walls. Stairs and walls have introduced torsional eccentricities, causing local failures of primary structural elements (Fig. 2). Out-of-phase relative responses of stair towers and structures have caused pounding and damage to separation joints, and stair towers have overturned (Fig. 3).

Damage to stairways has included failures of brittle enclosure materials which have littered or broken treads (Fig. 4), cracking and spalling of concrete at landings and walls, jammed exit doors, broken glass, dislocation of nonstructural components such as light fixtures or seismic joint coverplates, and disruption of building services. In some cases stairways have been inaccessible or unusable. Some stairways have been places of refuge during shaking; other stairways have caused injuries and fatalities.

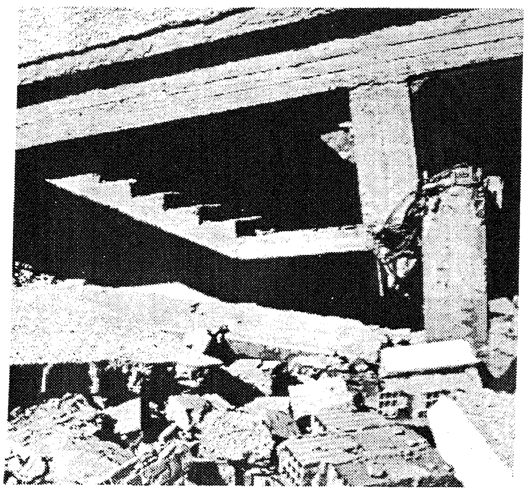

Fig. 1 Concrete column failure

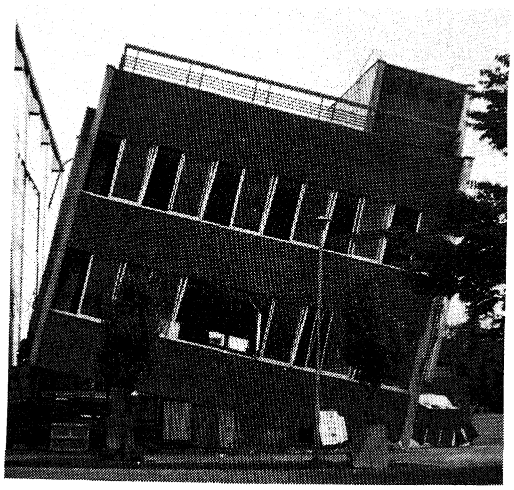

Fig. 2 Torsional effects

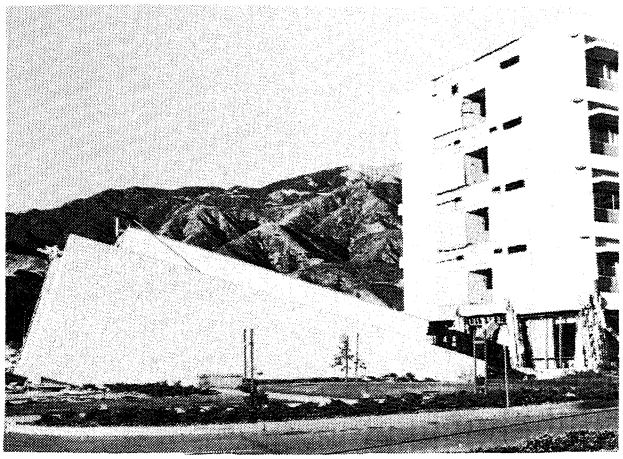

Fig. 3 Overturned stair tower

Fig. 4 Shattered wall

STAIRWAY PLANNING

Locations and arrangements of stairways result from design decisions on spatial organization and functional layout, internal circulation and emergency egress. For stairway systems intentionally designed to be part of the primary seismic resistant system, stairway shafts and other service cores are best distributed to avoid undesirable torsional effects, to balance the stiffness of the resistant elements with the mass. Especially problematic are stairway systems which act "unintentionally" as part of the primary structural system. These may significantly influence the initial elastic response of the building by their distribution and stiffness, and the inelastic response by their strength and ductility, producing unanticipated seismic behavior.

Movement characteristics of stairway structures must relate to those of the primary structural system. Stairways may be integrated in very stiff structures which protect them from damaging deformations. Stairways in ductile moment-resistant frame structures designed to stably dissipate seismic energy, may experience large deformations. These stairs may be isolated if stiff or integrated if having flexible enclosures and flights. Either structure deformations must be limited to those which the stair system can accommodate, or the stairways must be made tougher to withstand larger deformations. These deformations should be those which are expected in the actual building under real ground motions, not just those computed according to fictitious lateral forces defined by building codes.

Collaboration of architect and engineer in preliminary design phases can resolve basic configuration issues for stairways and establish the extent of stairway/structure interaction through selection of appropriate design strategies. Design proposals should be reviewed specifically to detect potential interactions and nonstructural elements which could cause undesired effects. When possible, the adequacy of the design should be verified through realistic analyses.

DESIGN STRATEGIES

Stairways can be structurally isolated as physically separate exterior towers, in enclosures mechanically isolated from the adjacent building frame, or as stairs with sliding joints at landings and walls. Isolation demands a clear understanding of the seismic response of the building and stairways in order to estimate with sufficient accuracy the necessary separations and appropriate interstory drift. By reducing interaction through carefully controlled connections or ductile isolators, damage and hazards could be considerably lessened, although the separated systems would still experience accelerations. Too small separations, because of the effects of impact (pounding), could worsen structural behavior rather than improve it. Separated stair tower foundations need special attention to withstand the large overturning forces which may be expected. Isolation strategies require consideration of materials, weatherproofing, fire and smoke infiltration, and maintenance to ensure effectiveness during the service life of the building.

Stairways may be integrated with the primary structural system to take advantage of the inherent stiffness characteristics of the stair as well as the enclosure walls. Stiffness contributions of some stair flights and landings may be assumed, but are usually not calculated, there being no easy method for this analysis. A stiff primary structure can protect stairways from damaging deformations. In a flexible system, integrated stairways can increase the stiffness of the structure substantially. This has advantages for controlling deformations, can result in an increase in overall lateral resistance, and may also lead to considerable increase in elastic strength. However, integration of stairway systems which lack sufficient strength to contribute usefully in a flexible primary structure, may create local problems and potential hazards.

STRUCTURAL ANALYSIS

For gravity load analysis a stairway is typically taken to be an independent system supported by the primary structural system in either a simple or a fixed manner. A single-flight stair is analyzed as if it were a simple beam, considering only flexural stresses. For lateral load analysis the initial elastic contribution of typical stairways to the behavior of the "total structure" could perhaps be approximately modeled as an equivalent assembly of rigidly connected beam or slab elements or as elements of a truss. But even if such an equivalent space frame approach provides sufficient accuracy, many stair/structure total systems would have to be modeled as complete three-dimensional assemblies to correctly analyze their interactions. Complications are added by openings, enclosures, complex stair geometries, and supports. The initial elastic detailed local behavior of a stairway system may be modeled using plate finite element analysis. Such detailed modeling of stairway systems within a "total" system offers an available, albeit cost-prohibitive, approach.

Rational design should be based upon analysis to predict the response of stairway systems to expected ground motions. The reliability of these analytical methods must be demonstrated experimentally, and the cost of analysis kept within practical limits. Simple methods are needed because complex studies may not be justified economically or technically. Structural engineers may need to decide for which stairway configurations costly analytical studies are warranted, and for which stairways standard details and provisions for construction and maintenance should be developed.

EXISTING SEISMIC CODES

Review of existing seismic code specifications (Ref. 2) reveals that few building codes directly refer to seismic design of stairways. Rather, stairways are implicitly included in provisions addressing the more general problems of seismic resistant design of architectural and nonstructural components, with primary emphasis on limiting interstory drift (or the effects thereof) of the primary structural system, and secondary emphasis on the actual seismic response of the component. These provisions, in effect, encourage analysis of the primary structural system without consideration of stairway/structure interactions. Furthermore, the actual response is estimated by an equivalent static lateral load that does not rationally account for interaction. In some codes a higher force factor is required for those elements (e.g., stairway enclosure walls) considered as part of the building's life safety system. These provisions may not be sufficiently specific for the important emergency functions of stairway system components.

MODEL CODE PROVISIONS FOR STAIRWAYS

In an ideal earthquake resistant design and construction code:

(a) The functions of stairways for regular service and emergency conditions should be stated, terms defined, and typical components identified.

(b) Conceptual guidelines for exit safety should be reviewed and modified to bring seismic safety issues forward. Structural guidelines should cover: advantages and disadvantages of integrating or isolating stairways; the effects of stairway distribution on the overall behavior of the primary structural system; selection of materials and construction to satisfy both fire and earthquake requirements; effects of stairways on the local behavior of structural and nonstructural components to which they are connected or come in contact during seismic excitation; selection and/or design guidelines for nonstructural components of stairways to control and limit damage.

(c) Minimum requirements should be established for structural analysis and design of stairways, considering both service load and extreme load conditions. For integrated stairway systems the code should refer directly to provisions for the primary structural system, clearly associating realistic load and load combination requirements with required deflection limitations, ductility requirements, and type of analysis (e.g., elastic or inelastic) to be used in evaluating member forces and deformations. Guidance on acceptable methods of analytically modeling the contribution of stairways to the total system response should be included. For isolated stairway systems the code should provide for analysis of the primary structural system to determine expected (realistic) system deformations that must be accommodated by the stairway system, and investigations needed to demonstrate that the proposed isolation technique will indeed accommodate the predicted deformations. The code should clearly establish acceptable means to model the seismic loadings and analytical methods to be used in evaluating the system response.

(d) The model code should set forth specific provisions regarding detailing and construction of the components of stairway systems, especially detailing between landings and their supports, and flights and landings.

(e) The model code should provide guidelines for identification of potentially hazardous stairways in existing structures, for evaluation of the degree of hazard, and for mitigation of these hazards.

GENERAL CONCLUSIONS

(a) Because stairways are the primary vertical emergency exit routes in multi-story buildings, they must be designed to ensure their use for safe egress and access during and after earthquakes.

(b) Jammed doors, debris-littered treads, detached components, and darkness are the most common hazards of stairway response to seismic shaking.

(c) Interactions of stairway structural systems with their nonstructural components and especially with the primary structural system have created much earthquake damage.

(d) Stair flights and enclosure walls have influenced, usually unintentionally, the dynamic characteristics and seismic responses of primary structures. Lack of attention to this problem has contributed to local structural damage and sometimes to structural collapse.

(e) Since stairways are often complex three-dimensional systems integrating a variety of architectural, structural, electrical, and mechanical components, their seismic behavior may involve complex interactions among these components.

(f) At present there exist no practical general analytical methods for predicting even the simplest aspects of stairway dynamic interaction with the primary structure. Few construction details for structural connections and assemblies have been experimentally evaluated for strong seismic shaking.

(g) Present U.S. seismic codes do not contain guidelines regarding stairway system selection, design or construction. Only a few foreign building codes specifically mention earthquake resistant stairway design.

(h) Current design practice relies upon prior projects and/or published recommendations which may not address seismic issues in a comprehensive manner. Yet the required high performance level for exitways makes stairway seismic design an important life safety concern.

RECOMMENDATIONS FOR IMMEDIATE IMPROVEMENTS

(a) Fuller understanding of stairway damage mechanisms requires more detailed information about, and analysis of, problems occurring in moderate and strong ground shaking. Reconnaissance and investigating teams should note stairway conditions, materials and construction, adjacent structural damage, possible interactions, and interference with evacuation. Post-earthquake studies should investigate human reactions and behaviors while exiting.

(b) Architectural design would benefit from consolidation of planning concepts for building configurations and stairway locations. Seismic implications of various architectural and structural plans should be studied and published so that designers may either avoid or consciously accommodate problematic schemes. Cost-benefit analyses of different design options should be considered in relation to seismic resistance, life safety, and property damage.

(c) The structural engineer in collaboration with the architect must consider the effects of stairway systems at early stages of the building design so that an appropriate structural strategy may be selected and applied. Professional handbooks and reference materials should be revised to include seismic implications of standard details.

(d) Seismic codes should include guidelines and comments about problems of interactions between stairways and primary structural systems. Omissions and ambiguities in specific requirements should be reduced so that designers using the code provisions could demonstrate the acceptability of their emergency egress schemes for earthquake hazards.

(e) Building officials should thoroughly review design calculations and drawings to ensure that proper design of stairways has been achieved.

(f) Development and dissemination of improved analytical methods will enable structural engineers to predict more accurately the stairway system response to be accommodated through proper selection of materials and detailing for stairways and their connections to the primary structure.

(g) Information about the anticipated stairway response must be communicated by the structural engineer to the architect, electrical engineer, mechanical engineer, and other consultants so that attachments, bracings, material assemblies, equipment characteristics, and damage limitations may be designed for expected displacements and accelerations.

(h) The concepts by which the exitways are designed should be communicated to the building owner, the occupants, and the maintenance staff so that expected building behavior during earthquakes may be anticipated, more comprehensive disaster response plans developed, and particular details or devices (such as separation joints) maintained as intended.

(i) Existing buildings should be inspected so that hazardous conditions in exitways can be removed or improved. This is especially important for any building which serves critical emergency functions or which has places of public assembly, high numbers of occupants, or hazardous contents.

RESEARCH NEEDS

(a) To improve the design and construction of new stairways and the repair and/or retrofit of existing stairways, a co-ordinated research program integrating literature and field surveys with analytical and experimental studies should be undertaken. This research program should (1) identify some stairway systems which show promising features for adequate fire and seismic performance; (2) initiate experimental studies to understand the behavior of stairway system components and assemblies and the interaction of specific stairway systems with primary structural systems; (3) devise experimental studies to improve methods and details of construction; (4) create matching analytical studies for rational mathematical idealizations of components and system behavior; and (5) develop simplified analysis and design procedures. The knowledge gained could lead to the development of new stairway systems as optimal solutions for specific building structural systems.

(b) Ideally, experimental studies of load-deformation behavior, carried into the inelastic range with load reversal, of typical stairway structural and enclosure components should be undertaken to develop analytical models that will serve as a basis for understanding real stairway system behavior. As the number and variety of even typical components are great, it may only be reasonable to investigate analytically the sensitivity of stairway seismic response to variations in the main parameters (components) by modeling the behavior of these components using available structural idealizations.

(c) Analytical studies should be undertaken to see if the initial elastic response of stairway structural systems alone and interacting with primary structures can be accurately modeled using available analytical techniques correlating predicted with measured behavior. Using plate finite elements, beam elements or a constraint approach might be considered. Studies should seek to develop methods of analysis, using existing techniques as much as possible, to model not only the behavior of isolated stairway systems but also the complete three-dimensional behavior of combined stairway/structural systems as well as detailed local behavior of stairway attachments to the primary structure.

(d) Because such elastic modeling techniques are of most use to the designer of stairway systems, the analytical studies should seek to develop simplified methods of analysis that may be implemented with available computer programs, and to produce design criteria (e.g., limit states for corresponding load conditions) for their application to practical problems of design.

(e) Analytical studies should be undertaken to see if aspects of nonlinear elastic and, particularly, nonlinear inelastic response behavior of stairway structural systems may be modeled with existing techniques. It is reasonable to initiate these studies after some experience with elastic modeling has been gained, using the nonlinear response studies to develop simplified practical methods that utilize linear elastic analysis techniques.

(f) Because stairway construction involves many nonstructural components which have suffered significant damage in past earthquakes, development of simplified methods of analysis and design of these components has become a pressing problem in recent years.

(g) The need to strengthen, demolish, or modify the use of existing hazardous buildings to improve life safety has been recognized as an important problem. Research efforts have been directed toward developing analytical methods to predict the behavior of existing buildings; consideration of stairway systems should be encouraged. Of special concern are unanticipated interactions and failures of brittle enclosure materials.

Finally, the main features and conclusions of research on the seismic performance of stairways should be compiled and made accessible to architects, engineers, and other design professionals. Design guidelines, structural strategy considerations, simple analytical methods, improved details, new construction techniques, and performance standards may reduce the amount of stairway damage encountered in future earthquakes and mitigate these hazards to human life.

ACKNOWLEDGMENTS

This paper summarizes research studies conducted with financial support from the National Science Foundation. Generous assistance in preparing this paper was provided by Professor Vitelmo V. Bertero, University of California at Berkeley, and Assistant Professor James W. Axley, University of Colorado at Boulder.

REFERENCES

1. Roha, C., J. W. Axley, and V. V. Bertero. The Performance of Stairways in Earthquakes. Report No. UCB/EERC-82/15. Berkeley: College of Engineering, University of California, September 1982.

2. International Association for Earthquake Engineering. Earthquake Resistant Regulations, A World List, 1980. Tokyo: Gakujutsu Bunken Fukyu-Kai, 1980.