EARTHQUAKE RESISTANT DESIGN OF REINFORCED CONCRETE STRUCTURES WITH EXTERNAL SHORT COLUMNS AND DEEP SPANDREL BEAMS

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SYNOPSIS

During recent earthquakes reinforced concrete structures with deep spandrel girders and short columns failed or sustained heavy damage particularly due to brittle shear failure of the columns. Reinforced concrete frames are classified according to their anticipated failure modes. Design procedures for these structures are reviewed critically and alternative methods are proposed.

INTRODUCTION

External frames made of monolithically constructed reinforced concrete columns and deep spandrel beams are often used as the main exterior frames and walls of buildings. Although designed according to present aseismic codes in order to resist the tributary vertical and lateral loads, these frames sustained, due to shear or shear-flexure failures of the short columns, heavy damage in recent earthquakes, (notably the 1968 Tockachi-Oki earthquake in Japan). The objective of this paper is to evaluate the potential earthquake response of spandrel-type structures as affected by the anticipated ultimate response of geometrically different load resisting elements and to develop suitable seismic load factors to prevent structural collapse under earthquakes.

CLASSIFICATION OF REINFORCED CONCRETE FRAMES

Based on a detailed evaluation of the response of r.c. framed buildings subjected to earthquakes and the results of laboratory studies (1) regular reinforced concrete building frames can be classified according to the anticipated failure modes as shown in Fig. 1. The shear, shear-flexure, or flexural failure modes occur in either the columns or beams and are primarily dependent upon the geometric terms α and β respectively. The term α is the ratio of free height: h, to width: d, of the columns, and β is the ratio of the span: ℓ to depth: D, of the beams. The shear failure mode with x-shaped cracks is very brittle and highly degrading due to a mostly inadequate stirrup reinforcement. The shear-flexure failure mode with inclined diagonal cracks at the ends of the beams or columns is more ductile than the shear mode but becomes unstable after the occurrence of the shear slip. The flexural failure mode is more ductile and less degrading than the previous modes of failure.

DETERMINATION OF THE EARTHQUAKE DESIGN LATERAL LOAD

Earthquake resistant design codes generally take into consideration

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the dynamic reliability and behavior of the structural system under earthquakes. Hence, the SEAOC Code (2) introduces a coefficient K in the base shear formula: V = base shear = KCW, where C and W are respectively a dynamic coefficient and the total tributary dead load of the frame. For most spandrel-framed structures having a height less than 160 feet a K factor equal to 1.0 is commonly used in the U.S. The use of a single coefficient K to represent the all important aseismic properties of the structure and its components is very restrictive and approximate. Logically there should be a relationship between the value of coefficient K and the potential mode of failure, the degree of degradation and the earthquake worthiness of the structure and its components. Referring to Fig. 1, the coefficient K should decrease as α and β are increased and the behavior of the frame becomes more ductile.

According to the SEAOC Code (2) a structure qualifies for lower values of K, such as K = 0.67, 0.80, or 1.00, if it has a "substantially complete vertical load carrying space frame". The probability of structural collapse under the action of a major earthquake becomes very small if, a) the vertical load-carrying system of the structure can survive the earthquake without its function being impaired, and b) the lateral load-resisting system of that structure can retain enough capacity to resist safely the lateral instability and future lateral loads. Therefore the present code requirement of "a substantially complete vertical load-carrying space frame" should be replaced by "a substantially complete earthquake-worthy vertical load-carrying space frame". The latter is defined as a vertical load-carrying space frame which does not substantially lose its safe vertical load-carrying capability during and after the action of a major earthquake. Hereafter, this type of space frame will simply be called an "EWVLC space frame".

The spandrel frames are the main part of the vertical load-carrying system of the structure even though in some cases interior load-bearing columns and frames also exist. The first step for determination of the K coefficient is to find out if the framing of the structure can be classified as EWVLC. The vertical load-carrying capability of the structural frame under earthquake action depends upon the potential seismic behavior of its components. If all these components can carry their share of vertical load safely under the earthquake action, then the entire frame can still be classified as EWVLC. If some of these components fail under the combined effect of vertical load and earthquake action, the frame cnn still be classified as EWVLC if the vertical load carrying capability of the whole frame or a substantial portion of it is not impaired. Brittle shear or shear associated flexural failure of columns, substantially reduces their vertical load-carrying capacity. Thus, any spandrel frame whose columns may suffer from this type of failure mode cannot be classified as EWVLC. If the columns remain elastic or if their failure is of the ductile bending type, then the brittle failure mode of other components of the frame such as beams and joints, must be investigated. If the failure of these components cause structural collapse; then the frame should be classified as NEWVLC (i.e. not EWVLC). However, if after failure of these components, the vertical loads are still transferred safely to the columns by other routes, the frame is EWVLC.

a) <u>K coefficient for structure with NEWVLC framing</u>: Most structures with types A, B, and C spandrel frames or with other types of nonductile reinforced concrete frames fall into this category. In this case the structure should be treated as a shear-bearing type structure. According to the SEOAC code, a coefficient K equal to 1.33 should be used for this type of structure. In addition the code recommends that any structure designed for a K value equal to 1.33 in one direction should be designed for the same value of K in the other direction. Furthermore, in the design of elements having a potential shearing or diagonal-tension failure mode, the ultimate design shear loading should be doubled.

b) K coefficient for structures with EWVLC framing: Types D and E spandrel frames can be designed as EWVLC frames. In this case, based on the SEAOC code, the following values for K may be used:

i) K = 0.67, if the EWVLC framing is designed as a ductile moment resisting (DMR) frame capable of resisting the entire lateral earthquake loading.

ii) K = 0.8, if the EWVLC framing is designed as a DMR frame capable of resisting at least 25% of the lateral earthquake loading. In addition the structure must have proper shear walls to resist the entire lateral loads.

iii) K = 1.0, if the EWVLC frame is not designed as a DMR frame, but the structure has proper shear walls to resist the entire lateral load. The height of this type of structure is limited to a maximum of 160 feet.

DESIGNING SPANDREL-TYPE STRUCTURES WITH EWVLC FRAMES

EWVLC frames must carry safely the vertical loads and accommodate the lateral displacements and forces induced by the earthquake action. When it is intended that these frames should resist the entire or a portion of the earthquake lateral loads, then these frames should be designed as ductile moment-resisting (DMR) frames. In this case the action and partial failure of spandrel walls must not impare the ductile behavior of the frame. This requirement can be achieved either by using fail-safe spandrel walls designed to fail before the shear level which would cause shear cracking of the columns is reached or by providing a suitable gap between the spandrel walls and columns to increase the effective length of the frame columns tend to prevent their brittle shear failure. When the EWVLC frames are not considered part of the lateral load resisting system and are thus primarily designed to support vertical loads, then the main design objective is to reduce the lateral stiffness of these frames in order to minimize the tributary lateral loads. One solution for this case may be to replace the short reinforced concrete columns by flexible steel or composite columns. A second solution is to use types D and E spandrel frames with long ductile columns instead of the brittle-type spandrel frames, types A, B, and C. A third solution more applicable to precast construction may be to provide proper hinges at the ends of columns and beams such that proper flexibility is achieved.

Determination of a technically and economically feasible solution for this design problem will require further extensive research and development efforts. Otherwise, the designer will have no choice but to design the spandrel-type structures with brittle NEWVLC frames and to use a higher design load factor.

REFERENCES

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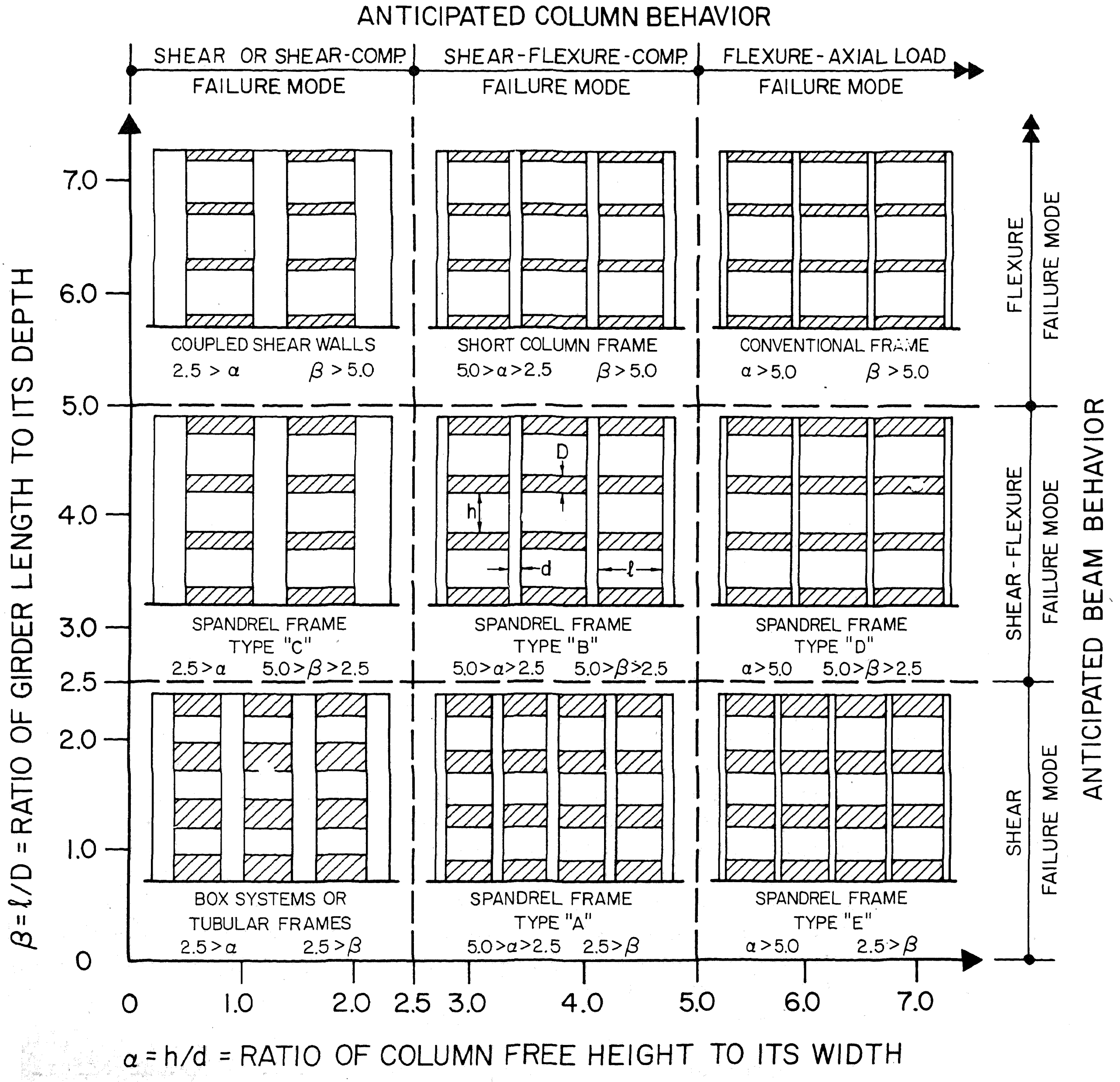

FIG. 1 VARIOUS TYPES OF FRAMES AND THEIR ANTICIPATED STRUCTURAL ACTION