SEISMIC DESIGN OF UNUSUAL IRREGULAR AND TALL BUILDINGS IN BRITISH COLUMBIA, CANADA

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The potential for a large earthquake to cause significant ground shaking has had a defining influence on the evolution of highrise buildings in British Columbia; however, unlike in the United States, structural steel systems and reinforced concrete moment-resisting-frame systems have rarely been used in Canada. Virtually all highrise buildings in British Columbia (BC) are concrete shear wall buildings. Older buildings, constructed up until the mid-1980s, typically have thin (200 mm or less) lightly-reinforced concrete walls distributed throughout the buildings.

Figure 1 summarizes how the earthquake demand that highrise buildings in Vancouver, BC must be designed for has changed over the past 40 years. The design spectral acceleration values specified by the National Building Code of Canada have been translated into the corresponding design spectral displacement values for buildings with a fundamental lateral period T = 2 s (about a 20-story building) and T = 4 s (about a 40-story building). The earthquake demands increased significantly in 1985, 1995 for tall buildings (T= 4 s), and in 2015. Today, the earthquake displacements that buildings must be designed for are more than four times what they were in 1975.

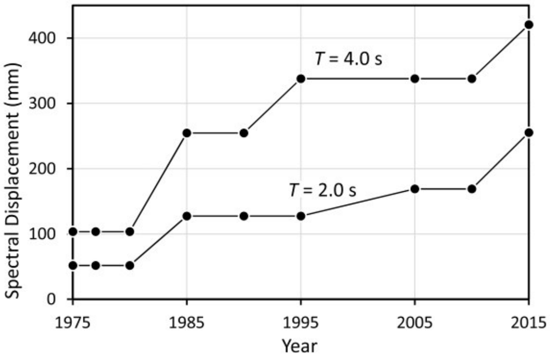

Fig. 1 – Summary of earthquake demands that highrise buildings in Vancouver have been designed for over the past 40 years

Adebar P, DeVall R, Mutrie J. "Evolution of Highrise Buildings in Vancouver, Canada," Structural Engineering International, Nr. 1, Feb. 2017, pp. 7-14.

In addition to the increased seismic demands described in Fig. 1, the changing requirements of the Canadian building code, caused a paradigm shift in the 1980s so that virtually all highrise buildings constructed in BC over the past 30 years have a large central core designed to resist all lateral loads. Typical modern BC highrise cores have three independent cantilever walls in one direction that are coupled in the transverse direction by ductile coupling beams above the door openings on each story.

Compared to other major cities, Vancouver has low height buildings because the City has restricted heights in order to protect public views of the North Shore Mountains, the downtown skyline, and the surrounding water. Recently, the City has relaxed the height restrictions in certain areas. Building heights up to 210 m are now permitted along the three primary streets of Georgia, Burrard and Granville within the Central Business District (CBD), as long as the building is not within any of the designated view corridors. The City also permits taller buildings in two prominent bridge "gateways" that mark the entry into downtown from the Burrard and Granville Bridges. The City of Vancouver has recently declared that the designs of highrise buildings must attain a new benchmark of architectural creativity. The recent designs that have been proposed for the city include very *unusual irregular* buildings that are much less likely to be habitable after an earthquake.

A type of irregularity that is showing up on an increasing number of high-rise buildings in British Columbia is inclined gravity-load columns. When inclined columns result in the gravity load causing a static overturning moment on the SFRS, the building has a gravity-induced lateral demand (GILD) type irregularity. On the other hand, if the inclined columns are arranged so that there is no net unbalanced horizontal force (due to gravity load) at the top and bottom of the inclined segments of the columns, no (static) gravity-induced lateral demand exists.

Preliminary results indicate there are two separate aspects of inclined columns that must be accounted for in the seismic design of buildings. The first has to do with the interaction of inclined columns with the gravity-load frames. Depending on the arrangement of the frame members, the inclined columns may result in increased deformation demands in gravity-load frames due to the lateral displacements of the building. In addition, depending on the stiffness of the frame members, gravity-load frames with inclined columns may have significant lateral stiffness. As a result, gravity-load frames with inclined columns may attract a significant portion of the lateral load applied to the building and/or the gravity-load frame may restrict the movements of the building.

The second, and more significant, way that inclined columns may influence the seismic response of buildings is due to differential horizontal accelerations at top and bottom of inclined columns causing vertical accelerations of the mass supported by the columns. While two gravity-load columns that are inclined in opposite directions may not apply a net horizontal static force to the SFRS, the inclined columns will still interact with the SFRS due to the rotational inertia of the vertical masses supported by the two columns. When one vertical mass is accelerated downward by the differential horizontal acceleration at the top and bottom of the inclined segment of the column, the other vertical mass will be accelerated upward by the second column being inclined in the opposite direction. The rotational inertia of one mass accelerating upward and the other mass accelerating downward is transferred to the SFRS by the structural elements that connect the inclined columns to the SFRS.

The influence of inclined gravity-load columns depends on the level of vertical mass that is supported by the columns and the stiffness of the structural elements that interconnect the top and bottom of the inclined segment of columns to the SFRS. To study this phenomenon, an example building was analyzed using response spectrum analysis by Mahmoodi (*PhD thesis, UBC, in progress*). The stiffness of the horizontal members connecting the top and bottom of the inclined columns to the SFRS were varied from very flexible to very rigid and results are summarized in Fig. 2.

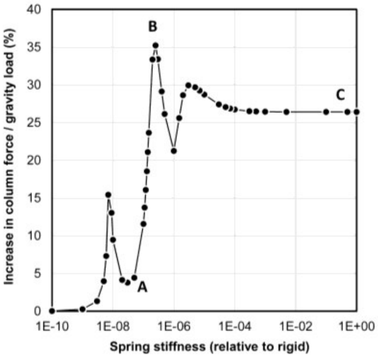

Fig. 2. Increase in forces resisted by inclined gravity-load columns as the stiffness of the elements connecting the top and bottom of the inclined columns to the seismic-force-resisting system of the building increase.

Adebar P, "Seismic Design of Highrise Concrete Shear Wall Buildings in Canada: Past, Present and Future," Seismic Effects on Buildings and Infrastructures, Proceedings of CSCEHKB Conference, Hong Kong, June 2017, 7 pp.

When the stiffness of the horizontal members connecting the inclined columns to the SFRS is very low (left side of Fig. 4), there is no interaction between the inclined columns and the SFRS. On the other hand, as the spring stiffness is increased, a strong interaction develops. The interaction can be expressed in terms of increased shear force applied to the SFRS or increased axial force applied to the inclined column due to the vertical acceleration of the mass. Fig. 4 shows the results for the increase in column force. When the horizontal members connecting the top and bottom of the inclined columns are infinitely rigid, the column force increases by 26% over the force calculated from gravity loads.

The conclusion from the preliminary study is that inclined columns need to be identified as an additional separate type of irregularity. It is proposed that inclined columns be identified as a new type of irregularity in the 2020 edition of NBCC.

ASEISMIC OF TRACK-BRIDGE SYSTEM OF HIGH-SPEED RAILWAY

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High-speed railway (HSR) are largely constructed in China for faster, safer and stable travelling. For HSR, bridges with ballastless track are frequently applied nowadays to overcome undulating terrain and provide a flat surface for high-speed travel. To meet the demand of economic development, the construction of high-speed railways are now extend to those high-intensity seismic zones. Therefore, the earthquake damage risk of these bridges are correspondingly increased. However, there are few relevant researches about the seismic performance and damage evaluation of high-speed railway bridge and existing achievements of regular bridges and highway bridges cannot applied directly to high-speed railway bridge. Therefore, specific works should been conducted for better solving these challenges.

In this study, the seismic performance test technology (quasi-static test, pseudo-dynamic test and shaking table test) and equipment (shaking tables) for high-speed railway bridge were developed. Moreover, high-speed train-track-bridge coupled vibration analysis method under earthquake excitation were also established. Based on above mentioned experiments and numerical analysis, the damage evolution law of components of track-bridge system in high-speed railway were studied. In addition, the mechanism and risk assessment of earthquake damage for high-speed railway track-bridge system were also revealed. In the end, based on dynamic behaviour, the seismic design method and seismic isolation technology for high-speed railway were developed.

Experimental and numerical results showed that the pier installed with fixed bearings was more susceptible to earthquakes than the other piers and fixed bearing is easily damaged as it cannot slide during the earthquake excitation. The shear studs in this study were more resilient to seismic loading than the other components. Specifically, all the maximum displacements of shear studs were still below threshold damage indices for repairable damage when the bridge experienced a 0.50 g PGA earthquake. In contrast, more attention should be given to the shear reinforcement bars (connecting the base plate and track plate), especially those installed on the continuous girder, as these are more easily damaged by an earthquake and may even be completely destroyed under a 0.50 g PGA earthquake. Moreover, the displacement of slide layer is slightly greater than that of the CA layer when subjected to the earthquakes (i.e. from the PGA scale of 0.20 g to 0.50 g), while both two layers are unlikely to be damaged by earthquake excitation with 0.50 g PGA. Based on the experimental and numerical results, the method of coupling vibration analysis for high-speed train-ballastless track-bridge system under earthquake excitation and corresponding analysis software were developed. Moreover, the relationship between the seismic response of bridge, track system and rail irregularity and the method of judging the train travel safety on HSR bridges were also established.