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Seismically induced cyclic buckling of steel columns including residual-stress and strain-rate effects

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ABSTRACT

Compression buckling tests were performed on four full-scale W-shaped column specimens to investigate the buckling response of columns in multi-storey braced steel frame structures subjected to seismic strong ground motions. The test protocols included monotonically and cyclically applied concentric and eccentric axial loading. One test was conducted under dynamic cyclic loading. End moments were applied on one cyclic test. The columns were W310 × 129 compact (class 1) sections made with ASTM A992 steel. Weak axis buckling was studied and the column had an effective slenderness ratio of 48. The response of the test columns was also examined using numerical simulations based on fibre discretization of the member cross-section. Column residual stresses and strain rate effects on the material properties were both characterized and accounted for in the numerical models. The study showed that steel columns can sustain several cycles of inelastic buckling under seismic induced loading while maintaining sufficient compressive resistance to support the applied gravity loads. Residual stresses affected the column response only at the first buckling occurrence with a gradual reduction of the columns' tangent stiffness prior to buckling as well as a reduction of the column's compressive resistance. High strain rates anticipated during strong earthquakes increased the column buckling and post-buckling strengths. The cyclic buckling response of steel columns can be predicted adequately when using nonlinear beam–column elements and cross-section fibre discretization provided that residual stresses and strain rate effects are included in the modelling.

1. Introduction

Large axial compression loads are expected to develop in columns of concentrically braced steel frames as a result of bracing members developing their probable compressive and tensile resistances when the structure is subjected to seismic strong ground motions [1]. Similarly, the yielding of link beams in eccentrically braced steel frames also induces high compression axial forces in columns. Capacity design requirements have been introduced in code seismic provisions to ascertain that the columns are provided with sufficient strength to support their tributary gravity loads together with the axial loads from the yielding components of the system [2–4]. In multi-storey buildings, the column design axial load at a given level is obtained by summing up the contribution of all yielding braces or links above the level under consideration, leading to very high axial loads in the columns that may considerably affect the overall cost of structures.

In reality, such large seismic axial load peak demands are expected to occur only a few times and to last for very short periods of time during a severe earthquake and the question can be asked whether steel columns could, under certain conditions, accommodate limited yielding excursions and/or even buckle without adverse loss in load carrying capacity. For instance, Newell and Uang [5] verified that columns can sustain a large cyclic plastic flexural demand without losing their axial load capacity. Similar experimental data for columns subjected to variable compression axial loads exceeding the column compressive resistance do not exist. Limited preliminary numerical simulations by the authors [6,7] indicate that current capacity design provisions for columns could be relaxed to some extent without a detrimental impact on the structural integrity. Such a relaxation, if permitted, could lead to substantial savings for new structures. The benefits could be extended to existing structures that have not been designed according to recently implemented capacity design methods and for which column strengthening represents a costly and challenging operation.

The seismic performance of structures designed for short duration buckling excursions must be carefully evaluated by means of probabilistic structural collapse assessment studies before such relaxation is implemented in practice. The methodology developed in the ATC-63 project [8] can be used to evaluate the margin of safety against structural collapse. The application of this

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Table 1
Buckling test program.

Test	Type	Loading rate	Loading
1	Monotonic	Quasi-static	Central
2	Cyclic	Quasi-static	Central
3	Cyclic	Dynamic	Central
4	Cyclic	Quasi-static	Eccentric

methodology requires a good understanding of the buckling response of columns under constant gravity loads and repeated additional compression due to seismic effects, together with robust numerical models that can reliably reproduce this behaviour. The nonlinear beam–column element with cross-section fibre discretization available in the OpenSees framework [9,10] has been used successfully to reproduce the cyclic buckling and tension yielding response of steel bracing members [11–13]. That model does not include residual stress effects. While residual stresses have limited effects on brace inelastic cyclic response and can be neglected if properly dealt with at the macroscopic level, they can lead to reductions of up to 30% of the compressive strength of structural steel columns made of shapes or built-up steel members [14], sufficient to make the difference as to whether or not a column will buckle under seismic loading. Lamarche and Tremblay [6,7] implemented residual stress effects in the OpenSees model and validated the implementation based on past compression tests on steel columns subjected to monotonic loading. Validation was still needed however for columns subjected to a cyclic buckling demand, including dynamic effects, as expected under seismic loading conditions.

This paper presents a test program that was carried out on four full-scale W-shaped steel columns that were subjected to four different displacement protocols producing inelastic buckling. Ancillary tests were conducted to obtain material properties under static and dynamic loading. The residual stresses were also measured using the sectioning method. The response of the column specimens was reproduced using the OpenSees nonlinear beam column including residual stresses. The axial load–deformation response, member end rotations and strain demand at critical locations are compared. The strain rate effects were evaluated using a fibre cross-section analysis program. The prediction of residual stress effects on column buckling strength with the OpenSees model are also validated against data from past tests on I-shaped built-up steel columns.

2. Test program

2.1. Objective and scope

In order to investigate the effects of residual stress and high strain rates on the pre- and post-buckling compressive cyclic behaviour of steel columns, full-scale centrally and eccentrically loaded column tests were performed. Four identical class 1 (compact) W310 × 129 columns made of ASTM A992 steel (F_y = 345 MPa) and 3725 mm tall were tested. The section and height of the specimens corresponded to typical storey heights encountered in braced steel framed buildings. The four buckling tests performed are summarized in Table 1. The experimental program included one monotonic quasi-static centrally loaded buckling test, one cyclic quasi-static centrally loaded buckling test, one cyclic dynamic centrally loaded buckling test, and, finally, one cyclic quasi-static eccentrically loaded buckling test.

Test 1 was performed according to Technical Memorandum #4 of the Guide to Stability Design Criteria for Metal Structures [15]. It aimed at obtaining the monotonic buckling curve of the W310 × 129 profile. Test 2 aimed at comparing the cyclic inelastic buckling curve to the buckling envelope obtained in Test 1. In Test 3, the same cyclic displacement protocol as in Test 2 was applied but at

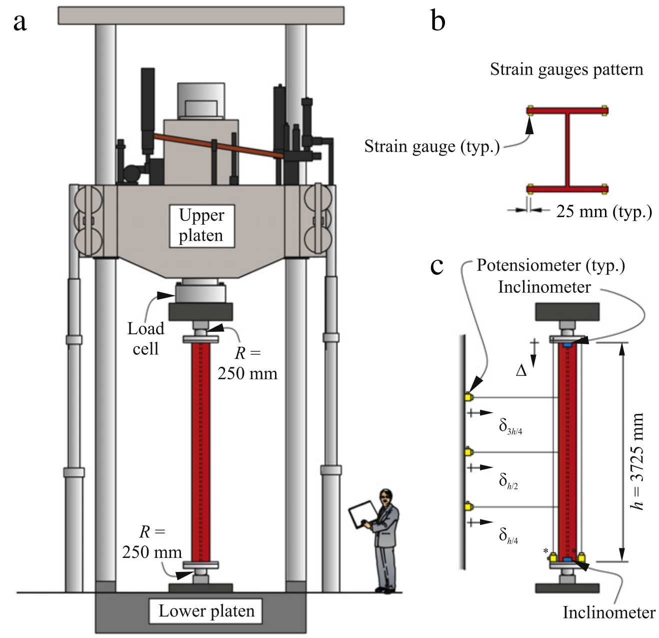

Fig. 1. Test set-up: (a) testing apparatus, (b) strain gauges' pattern at quarter-height and mid-height, (c) instrumentation. ∗ Two rows of potentiometers (four in total).

a faster rate more representative of a seismic loading history. The test was performed to investigate the effects of high strain rates on the cyclic buckling behaviour. Test 4 was performed to investigate the effects of combined axial load and end moments on the column cyclic buckling behaviour, as such conditions are more representative of the complex load combinations typically encountered in buildings during a seismic event. In all cyclic buckling tests, i.e., Tests 2, 3 and 4, an initial static load corresponding to approximately 60% of the nominal column compressive strength was initially applied on the columns to reproduce gravity load effects. Cyclically applied axial displacements were then applied a posteriori to simulate the seismic demand on a column in the post-buckling range up to a compressive axial deformation of 20 mm, corresponding to 0.53% of the column height. In the case of Test 3, the cyclic displacement protocol was dynamically applied assuming a building with a natural period of $T = 1$ s, typical of low- to mid-rise concentrically braced frames [12,16,17]. These types of building represent a vast proportion of the building stock in North America.

Ancillary tests included four tensile coupon tests to determine the material properties of the web and flanges, residual stress measurements, column initial out-of-straightness measurements in the plane of buckling, and high velocity tensile coupon tests to quantify the effects of strain rates on the column steel yield strength.

2.2. Test set-up and instrumentation

The column tests were performed in a 12 MN (2700 kip) capacity Tension/Compression MTS load frame in the Hydro-Québec Structural Engineering Laboratory at École Polytechnique de Montréal. The specimens were mounted between cylindrical bearings simulating pin-ended conditions for weak-axis buckling and fix-ended conditions for strong-axis buckling. These two 12 MN capacity hardened steel cylindrical hinges with 250 mm radii are illustrated in Fig. 1(a). These bearings were designed so that the centre of the cylinders coincides with the centroid of the column cross-sections at the column ends. Hence, the effective length of the column specimens about the weak axis was