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Peak and residual responses of steel moment-resisting and braced frames under pulse-like near-fault earthquakes

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ABSTRACT

This paper presents the behaviour of steel moment resisting and braced frames under pulse-like near-fault earthquakes. The key properties for characterizing near-fault ground motions with forward directivity and fling step effects are discussed, and the influence of varying brace properties on the key engineering demand parameters such as maximum inter-storey drift (MID), residual inter-storey drift (RID) and peak absolute floor acceleration (PA) is revealed. Among other findings, it is shown that the structural responses are related to spectral accelerations, PGV/PGA ratios, and the pulse period of near-fault ground motions. The moment resisting and self-centring braced frames (MRFs and SC-BRBFs) generally have comparable MID levels, while the buckling-restrained braced frames (BRBFs) tend to exhibit lower MIDs. Increasing the post-yield stiffness of the braces decreases the MID response. The SC-BRBFs generally have mean residual drifts less than 0.2% under all the considered ground motions. However, much larger RIDs are induced for the MRFs/BRBFs under the near-fault ground motions, suggesting that these structures may not be economically repairable after the earthquakes. From a non-structural performance point of view, the SC-BRBFs show much higher PA levels compared with the other structures. A good balance among the MID, RID, and PA responses can be achieved when “partial” SC-BRBs are used. To facilitate performance-based design, RID prediction models are finally proposed which enable an effective evaluation of the relationship between MID and RID.

1. Introduction

Steel moment resisting frames (MRFs) designed in accordance with modern codes are deemed to have satisfactory ductility, energy dissipation capacity, and collapse resistance against strong earthquakes. Steel braced frames are also a prevailing class of lateral load resisting structural system, although conventional steel braces are prone to global and local buckling under compression, which compromises their energy dissipation capability [1]. Alternatively, buckling-restrained braces (BRBs) have plump hysteretic behaviour under cyclic loading, and they have received great attention among seismic researchers and practitioners [2–5]. From a performance-based design point of view, however, the satisfactory seismic performance of both MRFs and buckling-restrained braced frames (BRBFs) are realised at the cost of considerable residual drifts with the damage occurring at major structural members such as beams, connection zones, and braces. An investigation carried out by McCormick et al. [6] suggested that a residual drift exceeding 0.5% after earthquakes may lead to prohibitively high repair cost for the structure, which, as a result, may have to be demolished. At the meantime, researchers revealed that the average residual drift for MRFs typically exceeds 0.5% and 1.0% under the design-based earthquake (DBE) and maximum considered earthquake (MCE), respectively [7,8], and these values can be even higher for BRBFs [9,10].

The emergence of self-centring buckling-restrained braces (SC-BRBs) enables improved seismic performance of steel braced frames. Employing posttensioning (PT) technology [11], Christopoulos et al. [12] and Chou et al. [13,14] successfully developed full-scale multi-core SC-BRBs which show stable flag-shaped hysteretic responses under cyclic loading. Zhou et al. [15] experimentally examined a new type of SC-BRBs utilising fibre-reinforced polymer composite tendons. The brace specimens were proved to meet the ductility, energy dissipation and self-centring requirements. Another promising material candidate for developing SC-BRBs is shape memory alloy (SMA) which is a novel class of metals capable of recovering large strains (up to 8–10%) immediately upon unloading [16–18]. It has been shown that SMA

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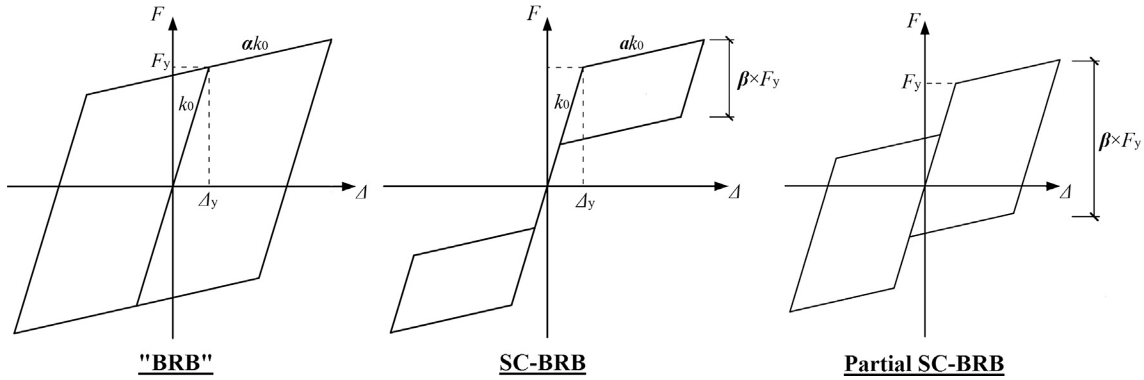

Fig. 1. Simplified hysteretic model of BRB, SC-BRB, and partial SC-BRB.

components can effectively provide self-centring and additional energy dissipation for SC-BRBs [19,20], and some researchers also consider SMA components for self-centring beam-to-column connections [21–25]. At system level, Moradi et al. [26] found that self-centring buckling-restrained braced frames (SC-BRBFs) and BRBFs have comparable maximum inter-storey drift responses, but the residual drift for the former is significantly reduced. Kari et al. [27] revealed that a combined use of both SC-BRBs and normal BRBs in a steel frame could effectively control the maximum drift whilst reducing the residual drift. A similar finding was reported by Eatherton et al. [28], where it was confirmed that structures can have negligible residual drift even if the brace itself exhibits certain 'static' residual deformation. Qiu and Zhu [29] warned that a high-mode effect tends to cause concentrated drift in the upper part of SC-BRBFs if the energy dissipation capability is insufficient.

It is clearly seen that a great progress has been made on understanding the fundamental seismic performance of steel MRFs and BRBFs. SC-BRBFs have also been attracting continuous research interests over the past decade. However, the existing studies paid insufficient attention on their behaviour under pulse-like near-fault ground motions, especially from the structural resilience point of view. Near-fault ground motions can be characterized by large, long-period velocity pulses in the fault-normal direction when the fault rupture propagates towards the site, normally with a speed close to the shear wave velocity. In this case, high amount of seismic energy is released in a short time at the 'forward-directivity' site, causing much higher demands for engineering structures compared with the case of far-field earthquakes [30,31]. 'Fling step', which occurs parallel to strike or dip directions, is another typical near-fault ground motion characteristic that is featured by a unidirectional large-amplitude velocity pulse with a permanent offset of the ground [32]. These characteristics have been recorded in a large number strong earthquakes, including the 1979 Imperial Valley, 1992 Landers, 1994 Northridge, 1995 Kobe, and 1999 Chi-Chi earthquakes, and have attracted significant attention among the community of structural engineers. Research focus has been mainly on the responses of idealised single-degree-of-freedom (SDOF) systems [33,34] and was later extended to more sophisticated structural systems including both fixed-base building frames [30,35–38] and based-isolated systems [39,40]. The behaviour of high-performance structural systems against pulse-like near-fault earthquakes has also been evaluated [41,42].

It has been recognized that pulse-like near-fault earthquakes generally induce larger inelastic deformation demand than far-field ones. In particular. the pulse effect could change the ductility and energy dissipation demands of multi-storey framed buildings, and thus affects the key engineering demand parameters such as maximum inter-storey drift (MID), maximum residual inter-storey drift (RID), and peak absolute floor acceleration (PA). Due to the pulse nature of near-fault ground motions, permanent drift may be more easily accumulated in structures with a full hysteretic response (e.g. MRFs and BRBFs), and the drift may be further accumulated during aftershocks. Therefore, the RID, which is one of the most important metrics indicating the potential damage level and the associated resilience performance, should be examined in detail. Although there is evidence that SC-BRBFs can effectively reduce RID under a wide range of ground motion types [43], the collapse resistance and serviceability performances (i.e., MID and PA) of these structures under near-fault earthquakes are not well understood. Furthermore, the sensitivity of BRBFs and SC-BRBFs to a number of key brace parameters (e.g., the post-yield stiffness and energy dissipation factor) under near-fault earthquakes is still unclear.

This paper sheds considerable light on the behaviour of steel moment-resisting and braced frame buildings under near-fault earthquakes. The prototype MRFs are three-storey and nine-storey steel office buildings (located in Los Angeles) designed as part of the SAC project [44]. For comparison purposes, the prototype MRFs are redesigned as braced steel frames according to ASCE 7-10 [45], enabling different types of braces with various bracing parameters to be considered. All the structures are designed based on design-compatible response spectrums with no particular consideration for near-fault pulse-like effects. These structures are then assessed in terms of MID, RID, and PA responses by using a suite of near-fault ground motion records, covering both forward directivity and fling step effects. This is followed by a detailed discussion on the influence of the varying brace parameters on the structural performance, and the observed trends are subsequently used for the proposal of practical RID prediction models.

2. Basic characteristics of SC-BRBs and BRBs

SC-BRBs, which can be achieved by either the PT or SMA technique, typically exhibit flag-shaped hysteretic behaviour. For an idealised flag-shaped curve as shown in Fig. 1, the axial load-deformation response first follows a linear path and then achieves a "yielding" point before advancing into the "post-yield" stage. Upon unloading, the load first decreases linearly and then enters into the unloading plateau and finally decreases to zero ideally with no residual displacement. It is noted that the "yielding" point is not caused by material yielding, but is instead triggered by decompression of the PT elements or by martensitic transformation of the SMA components. The energy dissipation, i.e., the area enveloped by the flag-shaped hysteresis, is contributed by extra energy dissipative devices (for the PT solution) or by inherent material damping (for the SMA solution).

The force-deformation relationship of a flag-shaped model is characterized by four key parameters, namely, initial stiffness k_0, yield strength F_y, post-yield stiffness ratio α, and energy dissipation factor β. In particular, the post-yield stiffness ratio (α) may vary significantly with different considered self-centring techniques. For instance, SMA components normally exhibit a pronounced post-yield stiffness (i.e., a large value of α) due to forward transformation slope and martensitic