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Buckling restrained braces as structural fuses for the seismic retrofit of reinforced concrete bridge bents

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ABSTRACT

A structural fuse concept is proposed in which easily replaceable ductile structural steel elements are added to an RC bridge bent to increase its strength and stiffness, and also designed to sustain the seismic demand and dissipate all the seismic energy through hysteretic behavior of the fuses, while keeping the RC bridge piers elastic. While this concept could be implemented in both new and existing bridges, the focus here is on the retrofit of non-ductile reinforced concrete bridge bents. Several types of structural fuses can be used and implemented in bridges; the focus in this paper is on using Buckling Restrained Braces (BRB) for the retrofit of RC bridge bents. The results of a parametric formulation conducted introducing key parameters for the design procedure of the fuse system, validated by nonlinear time history analyses are presented. A proposed design procedure, using BRBs as metallic structural fuses, is found to be sufficiently reliable to design structural fuse systems with satisfactory seismic performance. A graphical representation to help find admissible solutions is used, and shows that the region of admissible solution decreases when the frame strength ratio increases as a larger fuse element is required to achieve an effective structural fuse concept.

1. Introduction

Providing reliable mechanisms for dissipation of the destructive earthquake energy is key for the safety of structures against intense earthquakes. Inelastic deformations can limit the forces in members allowing reasonable design dimensions; and provide hysteretic energy dissipation to the system. The concept of designing some sacrificial members, dissipating the seismic energy, while preserving the integrity of other main components is known as the structural fuse concept. The structural "ductile" fuse concept was first introduced by Roeder and Popov [1] for the eccentrically braced frame concept for steel frames, although at that time the fuses were defined as a capacity design concept, and they were not easily replaceable. Fintel and Ghosh [2] used a similar capacity design concept and designated plastic hinging of the beams to be structural fuses. Wada et al. [3] expanded on the structural fuse concept by defining "damage-controlled" or "damage tolerant" structures. The approach stated that the structure should have two separate components, the first being a moment frame designed to resist gravity loads only. The second is a system of passive energy dissipation elements designed to resist loads resulting from strong ground motions. The damage controlled structures concept was further investigated and improved following the 1995 Northridge and 1995 Hyogoken-Nabu earthquakes by Conner et al. [4], who used steel shear panels and Buckling Restrained Braces (BRBs). That study demonstrated that it was possible to control the seismic response of a building by adjusting the distribution of stiffness and hysteretic damping of the fuses. Further developments were proposed by Shimizu et al. [5], Takana et al. [6], Wada and Haung [7], Haung et al. [8]. In particular, Wada and Haung [9] implemented an approach based on the balance of energy to design tall building structures having either hysteretic dampers or viscous dampers. A comprehensive study of damage controlled structures was performed by Wada et al. [10] who presented its potential to design new constructions and retrofit existing structures. Vargas and Bruneau [11,12] studied the implementation of the structural fuse concept using metallic dampers to improve the structural behavior of systems under seismic loads. A systematic and simplified design procedure to achieve and implement a structural fuse concept that would limit damage to disposable structural elements for any general structure, without the need for complex analyses was introduced based on identifying regions of admissible solutions for the structural fuse concept using nonlinear time history analyses.

All the previous work on the structural fuse concept focused on implementations on buildings; while inelastic deformations have been relied upon to achieve ductile performance for bridges, a rigorous implementation of the complete structural fuse concept

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Notations

The following symbols are used in this paper:

A_b	BRB cross sectional area
C_1	Modification factor to account for the influence of inelastic behavior on the response of the system
c	Yielding ratio of the BRB
D	Column diameter
E_s	BRB elasticity modulus
$f_{y\mathrm{BRB}}$	BRB yield strength
$f_c^{/}$	Concrete compressive strength
H	Frame height
K_{eff}	Elastic lateral stiffness of the bare frame
K_b	Elastic lateral stiffness of the BRBs
K_{tot}	Elastic lateral stiffness of the total system
L_b	Total length of BRB
L_{ysc}	Yielding length of BRB
L	Frame width
m	Mass of bent
n	Number of BRBs
R_d	Displacement magnification factor for short periods
S_a	Spectral acceleration demand
T_{eff}	Effective period of the total system
T_s	Period at the end of constant design spectral acceleration plateau
V_{yf}	Yield strength of the bare frame
V_{yb}	Yield strength of the BRB
V_{Df}	Maximum strength of the bare frame
V_{y1}	Total system yield strength
V_{y2}	Strength of the total system at the point of RC frame yielding
V_p	Lateral strength of the total system at the onset of column failure
V_e	Seismic demand on the total system if the system behaved elastically
V_i	Shear strength of the frame columns
V_n	Shear force consistent with the Load producing Flexure Failure of the frame columns
α	The ratio between the lateral stiffness of the BRB and the lateral stiffness of the bare frame
β	Post-yield strain hardening stiffness ratio of the bare frame
θ	BRB angle
Δ_{yb}	BRB yield displacement
Δ_{yf}	Bare frame yield displacement
Δ_{Df}	Lateral displacement at the onset of bare frame damage
δ_t	Expected displacement after frame retrofit (also called target displacement)
ε_b	BRB maximum strain demand
η	BRB strength ratio
ρ	Column reinforcement ratio
$\mu_{\max}$	Maximum displacement ductility that the total system can withstand
μ_f	Bare frame displacement ductility
μ_b	BRB displacement ductility
μ_D	Is the maximum local member displacement ductility demand
ξ	Frame strength ratio

has not been used for bridges. This could be of benefit for both new and existing bridges. The retrofitting approach is attractive given that seismically deficient bridges remain in service. Recent earthquakes in the United States, Japan and several other countries have demonstrated this seismic vulnerability, particularly for reinforced concrete bridges. These vulnerabilities have varied from total collapse, such as in the 1995 Kobe earthquake [13], to minor cracking and concrete spalling, such as in the 2001 Nisqually earthquake [14]. A common problem for RC bridge piers designed prior to the 1970's is that they were not detailed to prevent shear failure due to seismic excitation, nor detailed for ductile flexural response. For example, 13 mm (No. 4) ties or hoops spaced at 300 mm were typically used irrespective of column size, longitudinal reinforcement, or seismic demands. Also, short lap splices were used in column hoops and ties; as a result, these would open-up after concrete cover spalling during a severe earthquake that brought these structures into the inelastic range.

In this paper, building on this previous work, applicability of the structural fuse design methodology is investigated from a bridge engineering context (i.e., accounting for the need to protect bridge piers susceptible to non-ductile shear failures, defining zones of admissible solutions without resorting to non-linear time-history analyses, and providing modification factors that account for the characteristics of design spectra in bridge specifications). The methodology is presented based on simple hypotheses related to the mechanics of parallel non-coupled structural systems and static equilibrium equations, in the perspective that specially detailed ductile structural steel elements are directly added to the bridge bent to increase its strength and stiffness while not effecting the original lateral behavior of the columns (i.e. non-coupled lateral systems). The structural fuses are also designed to sustain the seismic demand and dissipate all the seismic energy through hysteretic behavior of the fuses, while keeping the bridge piers elastic. The intent of this concept is to make the fuse replaceable while the gravity load resisting system remains in service. Although this replaceability feature was not explicitly verified experimentally in the current project, Vargas and Bruneau [11,12] accomplished it for other types of structures.

Although adding the fuses will apply axial forces (tension or compression) that could impact the strength of the columns at the plastic hinge locations, this impact was not included in the design procedure presented in this paper. For most bridge columns, the axial forces applied by the fuses will be a negligible percentage of the column axial capacity (particularly given that bridge columns generally have a large axial capacity in comparison to building columns), but for those instances when that would not be the case, the engineer can consider the modified column capacity as a simple additional verification step in the procedures presented here. The general concepts and procedures presented here can also accommodate more complex material behaviors if so desirable for final design. Several types of structural fuses can be used and implemented in bridges; the focus in this paper will be on using the BRBs as a structural fuse. While many types of BRBs have been proposed in the past, one type of commonly encountered BRBs consists of a steel core encased in a steel tube filled with concrete. The steel core carries the axial load while the outer tube, via the concrete provides lateral support to the core and prevents global buckling. Typically a thin layer of material along the steel core/concrete interface eliminates shear transfer during the elongation and contraction of the steel core and also accommodates its lateral expansion when in compression (other strategies also exist to achieve the same effect). This gives the steel core the ability to contract and elongate freely within the confining steel/concrete-tube assembly. A variety of these braces having various materials and geometries have been proposed and studied extensively over the last 10–15 years [15–23]. A summary of much of the early development of BRBs which use a steel core inside a concrete filled steel tube is provided in Fujimoto et al. [24].