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Analysis of passively-damped coupled shear walls using continuum-based models

Hadi Moghadasi Faridani *, Antonio Capsoni

Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Leonardo da Vinci Square, 32, 20133 Milan, Italy

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ABSTRACT

This study assesses coupled shear walls (CSWs) equipped with passive damping systems using the damped continuum models developed as Coupled-Two-Beams (CTB). CTB models consisting of various distributed-parameter damping mechanisms are established. Numerical solutions for the dynamic analysis of these continuum systems are developed using a simple Finite Element (FE) model. It is illustrated how passive damping systems, viscous dampers and viscoelastic dampers, with various installation arrangements can be modeled with the use of the equivalent shear damping in a CTB system. Based on the dynamic analysis, the accuracy of damped CTBs with respect to different damping cases are verified. Two controlling parameters are introduced to evaluate the effect of both stiffness and supplementary damping on dynamical responses. The parametric study of passively-damped wall systems subjected to seismic loading is performed by emphasizing the effect of global bending and controlling parameters. Based on the important responses obtained from the dynamic analyses, optimal features of distributed damping such as damping length and its value are investigated with regard to the damping controlling parameter. This work shows that the developed CTB systems with the shear damping model are suitable tools for the dynamic analysis and the preliminary design of CSWs equipped with velocity-dependent dampers.

1. Introduction

Nowadays, different software packages are available for the exact analysis of structures based on a complete modeling. However, researchers and structural engineers usually look for simpler approaches when dealing with more complex structures. Hence, approximate analysis procedures are established in order to simplify the structural analysis and design. One of these procedures that is commonly introduced in the literature is the continuum method [1–5]. For building structures, this method basically leads to an idealized one-dimensional continuous model that is characterized by equivalent stiffness properties, properly representing the real stiffness of the structure. In the case of tall buildings, the cantilevered beam may quite naturally arise as a reference continuum model. The classical cantilevered beams mainly include Euler-Bernoulli Beam (EBB); Shear Beam; Timoshenko Beam (TB); Sandwich Beam; and Coupled-Two-Beams (CTB) [5].

In addition to the stiffness characterization that is addressed frequently in continuum models [4], damping features can also be established by means of distributed-parameter models. In this case, a consistent continuum-based definition seems to be useful not only for a proper analysis of inherent damping in the structure but also for the assessment of supplementary passive damping [6–8]. A comprehensive overview on the most-used damping models in continuous beams can be found in the literature [9–13].

Distributed damping models were established [14–16] to study energy dissipation mechanisms in Euler-Bernoulli Beams (EBB) which are simple systems suitable as the first approach in modeling tall buildings. Both external viscous damping and internal viscous damping models distributed along the EBB were studied.

In order to capture the dynamic behavior of shear-type buildings (frames), different damping models were discussed based on the Shear Beam formulation. It was recommended to use the equal modal damping model in structures with no energy dissipating devices or with friction-type dissipators. In addition, the internal damping in the Shear Beam could be applied where energy dissipating devices, e.g., linear viscous dampers, exist in structures [17]. The evaluation of dynamic responses affected by continuous damping models in Timoshenko beams (TB) was found an active research topic [18–20]. Such beam systems were used to equivalently model shear walls or trussed resisting schemes. The location and the length of damped segments in TBs with partially

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* Corresponding author.
E-mail address: hadi.moghadasi@polimi.it (H. Moghadasi Faridani).

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Nomenclature

A_1, A_2	cross-section areas of left and right walls
A_b, A_c	area of connecting beams and continuum core
B_1, B_2	width of left and right walls
CSW	Coupled Shear Wall
CTB	Coupled-Two-Beams
DIVD	Distributed Internal Viscous Damping
EBB	Euler-Bernoulli Beam
QEP	Quadratic Eigenvalues Problem
RC	Rotational Constraint in CTB
TB	Timoshenko Beam
C	global damping matrix
C_e	damping matrix of e^{th} FE
C_{add}, $C_{5\%}$	resultant value of passive damping and of 5% inherent damping
c	classical viscous damping
c_b	bending damping
c_d	viscous damping coefficient in dampers
c_{eq}	equivalent shear damping in CTB
c_s	shear damping
E	elastic Young's modulus
F	global force vector
F_e	generalized force vector of e^{th} FE
$f(x,t)$	distributed transverse load
G	elastic shear modulus
G_{eq}	equivalent shear modulus in continuum model
G'	shear storage of viscoelastic material
G''	loss modulus of viscoelastic material
h, h_b	story height and depth of connecting beams
I_1, I_2	moments of inertia of left and right walls
I_b, I_c	moment of inertia of connecting beams and of continuum core
$Im(\omega_1)$	oscillating part of fundamental mode
K	global stiffness matrix
K_e	stiffness matrix of e^{th} FE
K_{a1}	equivalent axial stiffness of walls
K_{b1}	sum of flexural stiffnesses of walls
K_{s1}	sum of shear stiffnesses of walls
K_{s2}	equivalent shear stiffness of core
k_d	stiffness coefficient in dampers
k_{eq}	equivalent shear stiffness in CTB
$\mathcal{L}$	Lagrangian
L	total height
L_d	length of equivalent distributed passive damping in CTB
ℓ	length of e^{th} FE
ℓ_b, ℓ'_b	free and modified length of connecting beams
M	global mass matrix
M_e	mass matrix of e^{th} FE
$m(x)$	space-dependent distributed mass density
$\bar{m}$	distributed mass along the height coming from floor masses
$N(x)$	shape functions matrix containing linear function interpolations
$q, \dot{q}$	generalized displacement and velocity fields
$\mathcal{R}$	Rayleigh Dissipation Function
$Real(\omega_1)$	decay rate of fundamental mode
$s_e(x,t)$	generalized displacement vector
$\mathcal{T}$	Kinetic Energy
$Temp$	temperature in viscoelastic material
t	thickness of connecting beams
U_e	nodal displacement vector of e^{th} FE
u, $\dot{u}$	transverse displacement and velocity
$\ddot{u}_g(t)$	ground acceleration
$\mathcal{V}$	Potential Energy
$\mathcal{W}$	work produced by external load
$w, \dot{w}$	axial displacement and velocity in walls
β	dimensionless coordinate in FE
φ_i	natural i^{th} mode shape
γ	shear strain in viscoelastic material
γ_u, γ_θ, γ_w	horizontal, rotational, and vertical mass of walls
η	controlling parameter of passive damping
κ	shear correction factor
λ	controlling parameter for three-field CTB
λ^*	controlling parameter without global bending effect in CSWs
μ	modification coefficient of connecting beam length
ω_i	natural frequency associated to i^{th} mode
$\bar{\omega}_i$	complex eigenvalues associated to i^{th} mode
$\omega_{d,1,}$ $\omega_{N,1}$	damped and natural frequency of fundamental mode
$\rho, \dot{\rho}$	rotation in continuum core and its rate
ρ_d; ρ_c	walls and core masses per unit volume
$\theta, \dot{\theta}$	rotation and its rate in walls

Distributed Internal Viscous Damping (DIVD) was investigated by several researchers [21–25].

Theories of Sandwich Beams, as more advanced beam systems compared to EBBs and TBs, were applied for the analysis of composite structures in which the effect of viscoelastic distributed damping layers on vibrational and dynamical responses was reported by several researchers [26–33]. Such beam models were introduced appropriately for modeling and analyzing various building structural systems, e.g., coupled shear walls, frames, and a combination of several systems [2]. Also, Coupled-Two-Beams (CTB) consisting of a flexural beam and a shear beam was proposed for modeling building structures, where the velocity-dependent viscous damping and equivalent modal damping ratio were used to model inherent energy dissipation mechanism [34]. Tarjan and Kollar [35] exclusively proposed the estimation of modal quantities of damping in various continuous beams, without proposing the physical damping models in such systems.

In terms of passive damping modeling in coupled shear walls (CSWs), the efficiency of viscous dampers as coupling elements was assessed based on a shear-type damping proposed for a continuum model with the flexural behavior (EBB) [36]. A semi-analytical solution followed by a complex modal spectral analysis was developed for the response assessment. The full distribution of damping along the height was considered, without addressing the optimization aspects of the damping model. Tokarev and Lavan [37] further developed the continuum model for the seismic design of coupled walls or trusses with viscous dampers placed in discrete positions along the height. Based on the concept of a cantilever EBB equipped with a rotational damping as the equivalent model of a damper, some non-dimensional controlling parameters were defined and a parametric study using the complex modal spectral analysis was performed to analyze important responses with respect to the damping value and its location throughout the height. The authors concluded that the most efficient location for discrete dampers was around the top, resulting in more reductions in responses and higher forces in the dampers.

More recently, damped beam systems capable of modeling CSWs equipped with velocity-dependent dampers were proposed [38–40]. The distributed-parameter damping mechanisms in these systems were theoretically exploited in order to properly achieve dynamic responses in both inherently-damped and supplementary passively-damped configurations. In addition to the linear