Engineering Structures 56 (2013) 919–934

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental characterization and modeling of energy dissipation in reinforced concrete beams subjected to cyclic loading

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ARTICLE INFO

Article history:
Received 9 February 2013
Revised 12 June 2013
Accepted 14 June 2013
Available online 17 July 2013

Keywords:
Damping
Three point bending tests
Damage model
Reinforced concrete
Reverse cyclic loading

ABSTRACT

The way of modeling the damping phenomenon in nonlinear time history analysis is still an opened question and remains a motivating challenge in the scientific community. The well-known approach lies in considering non-physical viscous forces that are proportional to the velocity field. A damping matrix must be defined and its identification is not based on physical considerations. This study aims at exploring the possibility of identifying a local constitutive model in order to account for damping in a natural way. To reach this objective, an experimental campaign based on reinforced concrete beams subjected to reverse three-point bending tests is presented. These results allow identifying in an accurate way the hysteretic scheme used to take into account the hysteretic phenomenon. In particular, an ad hoc hysteretic scheme is shown to be consistent in terms of energy dissipation. Numerical free vibration tests are then carried out in order to demonstrate that the use of a viscous damping can be avoided if the local constitutive concrete model accounting for hysteretic phenomenon is accurately identified.

1. Introduction

When considering time excitation loading applied to a mechanical system, a damping phenomenon is observed. The way of modeling this damping phenomenon is still an open question and remains a motivating challenge in the scientific community. Nowadays, several sources of damping have been identified and related phenomena are recognized as contributing factors to the overall damping phenomenon. In the case of concrete or reinforced concrete one can point out (i) the frictional sliding between the surfaces of the crack, (ii) the bond at the steel/concrete interface that may induce residual displacements, (iii) the radiation damping and (iv), the energy dissipation at connections or the dissipation due to non-structural components.

Classically, damping is modeled in a global and non-physical way by considering additional viscous forces in the momentum balance equation. A so-called viscous damping matrix accounting for several contributing phenomena, responsible for energy dissipation is introduced. Such a damping matrix is considered for example in the engineering practice, in a design context, to describe the effects of highly dissipative phenomena such as cracking and other sources of energy dissipation. In such a case, linear or quasi-linear structural models are used to predict the time history response of a given structure. Typically 5% viscous damping ratio for concrete structures is considered to cover all sources of damping up to member yielding, including concrete cracking.

The most common linear viscous damping model is the Rayleigh's damping model [1] described in [2] which is a particular case from the Caughey series [3]:

$$C = \alpha M + \beta K \quad (1)$$

where C is the damping matrix, α and β are scalar parameters identified from the two first modal frequencies, M is the mass matrix and K is the stiffness matrix. This damping model is directly proportional to the mass and to the original stiffness of the structure. A rheological interpretation of this type of damping is presented in Fig. 1a.

A damping matrix of the form presented in (1) is also largely used in nonlinear time history analysis. Recent works [4–8], have demonstrated that the use of a viscous damping model, in the frame of nonlinear time history analysis, often leads to inaccurate estimations of displacement and internal forces in the structure.

In such analysis, several improvements can however be applied to the well-known Rayleigh's damping. The most common is to replace the initial stiffness by the tangent stiffness [9–11]. This approach allows taking into account the damping evolution as a function of the damage state of the structure. It gives better results

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http://dx.doi.org/10.1016/j.engstruct.2013.06.024

Nomenclature

English alphabet

C	damping matrix
D_1	scalar tension damage variable
D_2	scalar compression damage variable
E	Young modulus
E_0	initial Young modulus
$G_1(z_1)$	hardening function for concrete in tension
$G_2(z_2)$	hardening function for concrete in compression
H	consolidation function
K	stiffness matrix
M	mass matrix
R	consolidation function for steel
R_0	control the transition from elastic to plastic branches
Y	energy rate released for damage activation
Y_1	energy rate released for damage in tension activation
Y_2	energy rate released for damage in compression activation
Y_0	initial threshold for damage activation
Y_{01}	initial threshold for tension activation
Y_{02}	initial threshold for compression activation
Z	thermodynamics force associated with damage
Z_1	thermodynamics force associated with damage in tension
Z_2	thermodynamics force associated with damage in compression
a_R	plastic hardening modulus 1
b	strain-hardening ratio
b_R	plastic hardening modulus 2
d	scalar damage variable
E_c	experimental concrete Young modulus
E_s	experimental steel Young modulus
f_{cm}	concrete compressive strength
f_{tm}	concrete tensile strength
f_u	steel ultimate strength
f_y	steel yielding strength
k_{eff}	effective stiffness
p	cumulative plastic strain
$u(x)$	axial displacement
$v(x)$	transverse displacement
z	isotropic hardening variable

Greek alphabet

α	mass coefficient for damping matrix
β	stiffness coefficient for damping matrix
β_1	coefficient related to the tension inelastic strains
β_2	coefficient related to the compression inelastic strains
γ	kinematic hardening modulus 1
ε	strain
ε^p	permanent strain
ε^π	internal sliding strain
ε_u	ultimate strain
ε_{xx}	normal local strain
ε_{xy}	shear local strain
ε_y	yield strain
η	closure variable
$\theta(x)$	rotation
λ	load ratio
λ_s	maximum load ratio of a block
υ	Poisson's ratio
ξ_{eq}	equivalent damping ratio
ψ	Helmotz free energy
ρ	material density
ϱ	kinematic hardening modulus 2
σ	stress
σ^+	positive part of the stress
σ^-	negative part of the stress
σ_c	compressive strength
σ_f	mean closure stress
σ_y	yield stress
σ_u	ultimate stress
χ	Gibbs free enthalpy

Acronym

B500B	steel class according to eurocode
C30/37	concrete class according to eurocode

in the low frequency range but problems remain in high frequency region, as one can notice in Fig. 1b. Another approach lies in updating the coefficients α and β. This method produces damping ratios that are close to the experimental ones. However it needs to recompute the modal frequencies at each computational step which is not practical [12].

From the above discussion, it is clear that modeling the damping phenomenon properly is still nowadays not an easy task. This study aims at exploring the possibility to identify better local constitutive models in order to account for damping in a natural way, leading to a drastic reduction of the viscous damping matrix contribution. In fact, the choice of the laws used to model the damping mechanisms will have a great influence on the results of the numerical analysis. A key point is that the concrete constitutive law accounts for hysteretic phenomena. Nevertheless, the hysteretic scheme needs to be identified properly. To do so, an experimental campaign has been carried out in order to acquire appropriate experimental data related to energy dissipation in RC

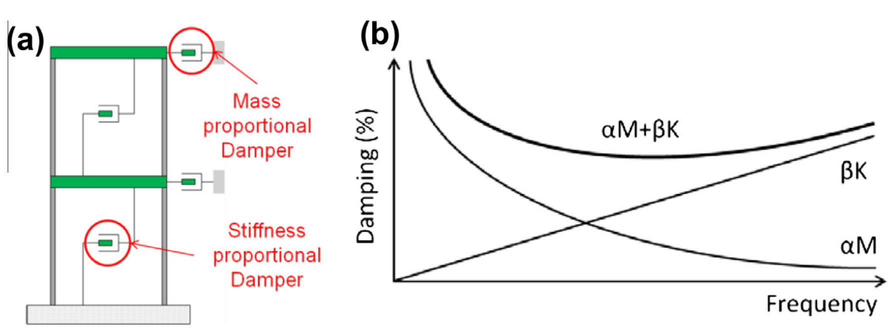

Fig. 1. (a) Physical interpretation of the Rayleigh's damping and (b) Rayleigh's damping ratio/frequency curve.