Structural Safety 76 (2019) 95–107

Contents lists available at ScienceDirect

Structural Safety

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

Probabilistic Theory of Plastic Mechanism Control for Steel Moment Resisting Frames

Vincenzo Piluso[a], Alessandro Pisapia[a], Paolo Castaldo[b], Elide Nastri[a,*]

[a] University of Salerno, Dept. Civil Engineering, Italy

[b] Department of Structural, Geotechnical and Building Engineering (DISEG), Politcecnico di Torino, Turin, Italy

ARTICLE INFO

Keywords:
Collapse mechanisms
Stochastic frames
Material uncertainty
Probability of failure
Binary systems

ABSTRACT

This work aims at the development of an advanced method for the seismic design of Moment Resisting Frames (MRFs) based on a target value of the failure probability in the attainment of a collapse mechanism of global type for stochastic frames (considering the aleatoric uncertainty of the material properties). Therefore, the method herein presented constitutes the probabilistic version of the Theory of Plastic Mechanism Control (TPMC) already developed for frames with deterministic material properties. With reference to MRFs whose members have random values of the yield strength, when structural collapse is of concern, the failure domain is related to all the possible collapse mechanisms. Within the probabilistic TPMC, the term "failure" does not mean the attainment of a structural collapse, but the development of a collapse mechanism different from the global one.

The design requirements normally needed to prevent undesired collapse mechanisms are probabilistic events within the framework of the kinematic theorem of plastic collapse. The limit state function corresponding to each event is represented by a hyperplane in the space of random variables, so that the failure domain is a surface resulting from the intersection of the hyperplanes corresponding to the limit states representing the single failure events. Since plastic hinges in frame's members are common to many different mechanisms, the single limit state events are correlated. Therefore, by applying the theory of binary systems and considering that the limit states are events located in series, the probability of failure can be computed by means of Ditlevsen bounds. This approach has been validated by means of Monte Carlo simulations.

In order to achieve a predefined level of reliability in the attainment of the design goal, the reliability analysis is repeated for increasing values of the overstrength factor of the dissipative zones to be used in TPMC, aiming to its calibration. Finally, on the basis of the results of a parametric analysis, a simple relationship to compute the value of the overstrength factor needed to include the influence of random material variability in the application of TPMC is proposed.

1. Introduction

It is well known that the control of the collapse mechanism is of primary importance in the seismic design of structures to assure adequate global ductility and energy dissipation capacity. Specifically, structures exhibiting soft storey or partial mechanisms are not able to exploit their plastic reserves and are subjected to damage concentration phenomena. For this reason, it is universally recognised that the optimum seismic performances are obtained when a collapse mechanism of global type occurs. Modern seismic codes (Eurocode 8, AISC) [1,2] provide simplified design rules to prevent unsatisfactory collapse mechanisms, such as the use of the so-called beam-column hierarchy criterion (strong column-weak beam design methodology according to American terminology) for Moment Resisting Frames (MRFs). However, this criterion is usually able to prevent soft storey mechanism only, but it does not assure the development of a collapse mechanism of global type [3,4]. In order to overcome the drawbacks of code provisions, the Theory of Plastic Mechanism Control (TPMC) has been developed [3,4] by extending the kinematic theorem of plastic collapse to the concept of mechanism equilibrium curve. Such approach, including the influence of second order effects, allowed the definition of the design conditions to prevent all the undesired collapse mechanisms, up to an ultimate displacement compatible with the local ductility supply of structural members.

Up to now, TPMC has been already applied to deterministic structures having different seismic resistant schemes [5–11] and structural material [12]. The reason of the success relies on the robustness of the theoretical background based on the kinematic theorem of plastic

* Corresponding author.
E-mail addresses: v.piluso@unisa.it (V. Piluso), alpisapia@unisa.it (A. Pisapia), paolo.castaldo@polito.it (P. Castaldo), enastri@unisa.it (E. Nastri).

https://doi.org/10.1016/j.strusafe.2018.08.003
Received 19 February 2018; Received in revised form 17 June 2018; Accepted 22 August 2018

Nomenclature

$\alpha_0^{(g)}$	First order collapse mechanism multiplier of horizontal forces for the global mechanism
$\alpha_{0.i_b.i_t}^{(t)}$	First order collapse mechanism multiplier of horizontal forces for the generic mechanism
$\boldsymbol{\beta}_C$	Vector of reliability (or Cornell) indexes
$\gamma^{(g)}$	The slope of the mechanism equilibrium curves for the global mechanism
$\gamma_{i_b.i_t}^{(t)}$	The slope of the mechanism equilibrium curves for the generic mechanism
γ_{ov}	Overstrength factor
$\boldsymbol{\Gamma}^{(sb)}$	Vector of coefficients accounting for second order effects in case of global mechanism and shear band mechanisms
$\boldsymbol{\Gamma}^{(up)}$	Vector of coefficients accounting for second order effects in case of global mechanism and upper partial mechanisms
δ	Top sway displacement
δ_u	The design displacement compatible with the ductility supply of the structure
μ_G	Mean value of G
$\boldsymbol{\mu}_x$	Vector of means of **x**
ρ	Correlation coefficient between y_1 and y_2
ρ_{ij}	Correlation coefficient between i-th and j-th events
σ_G	Standard deviation of G
σ_G^2	Covariance matrix of G
Φ	Standard Gaussian CDF
a_0	Vector the known quantities
$\mathbf{b}_i$, $\boldsymbol{b}_j$	i-th and j-th row of **B** matrix
B	Matrix of deterministic coefficients
$\mathbf{B}_b^{(sb)}$	Submatrix of coefficients of sum of the plastic moments of beams at each storey with reference to events related to the “shear band” mechanisms
$\mathbf{B}_c^{(sb)}$	Submatrix of coefficients of sum of the plastic moments of columns at each storey with reference to events related to the “shear band” mechanisms
$\mathbf{B}_b^{(up)}$	Submatrix of coefficients of sum of the plastic moments of beams at each storey with reference to events related to the “upper partial” mechanisms
$\mathbf{B}_c^{(up)}$	Submatrix of coefficients of sum of the plastic moments of columns at each storey with reference to events related to the “upper partial” mechanisms
cov	Coefficient of variation
$\mathbf{C_x}$	Vector of covariance of **x**
$E[\,]$	Linear operator (expected value)
$E_{i_b.i_t}^{(t)}$	Failure event
F_k	The seismic force applied at k-th storey
$G(\mathbf{x})$	Function of the random vector **x**
h_k	Storey height of the k-th storey
h_{i_b}, h_{i_t}	Storey height of the i_b-th storey or i_t-th storey
h_{n_s}	Sum of the interstorey heights of the storeys involved by the generic mechanism
i	Column index
i_b, i_t	Mechanism index
j	Bay index
k	Storey index
$M_{b.j.k}$	The plastic moment of the beam of j-th bay at k-th storey
$M_{c.i.k}$	the plastic moment of i-th column of k-th storey
n	Size of the frame sample in MC simulation
n_0	Number of the failure cases in MC simulation
n_b	Number of bays for each storey
n_c	Number of columns for each storey
n_s	Number of storeys
N_{tot}	Total number of possible mechanisms
$\boldsymbol{p}_f$	Vector of probability of the failure events
P_f	Probability of failure
$P_{f.i}$	Probability of failure of i-th event
$P_{f.ij}$	Joint probabilities between i-th and j-th events
R	Reliability factor
sb	Shear band mechanisms
t	Mechanism index
up	Upper partial mechanisms
V_k	The total gravity load applied at k-th storey
x	Vector random variables
$\mathbf{x}_b$	Vector collecting the sum of the plastic moments of beams at each storey
$\mathbf{x}_c$	Vector collecting the sum of the plastic moments of columns at each storey
y_1, y_2	Independent standard Gaussian variables

collapse and on second order rigid plastic analysis. However, even in the case of structures designed by TPMC, undesired collapse mechanisms could occur when the effects of random material variability are taken into account. This is the case of stochastic steel frames, whose members have random plastic moments due to the aleatoric uncertainty of the yield strength of steel.

The problem of undesired effects in plastic mechanism control, due to random material uncertainty, are also recognised by modern seismic codes that, aiming to compensate such effects, suggest the use of overstrength factors for the evaluation of the ultimate resistance of dissipative zones within hierarchy criteria. As an example, ANSI/AISC 341-10 [2] computes the ultimate resistance of dissipative zones covering the effects of uncertainty of yield strength by means of a factor given by the ratio between the average yield strength of steel and its nominal value. This is the so-called overstrength factor in material yield stress, denoted with R_y in ANSI/AISC 341-10. Conversely, Eurocode 8 [1] provides an overstrength factor γ_{ov} (having the same aim of R_y) ranging between 1.0 and 1.25. However, these values, applied within the beam-column hierarchy criterion, are not based on a probabilistic assessment aimed at a specific collapse mechanism.

It is also useful to point out that the overstrength factor, γ_{ov} according to EC8 or R_y according to ANSI-AISC 341-10, refers to the overstrength due to the random variability of yield stress. Conversely, the system overstrength Ω_0, adopted both in ANSI-AISC 341-10 [2] and ASCE 7-10 [39] is related to the overall plastic redistribution capacity of the structural scheme.

In this work, the attention is focused on the calibration of γ_{ov} (or R_y) with the aim to properly accounting for the influence of random material variability (i.e., yield stress variability) on the control of the collapse mechanism typology.

As in the last two decades many researchers devoted their efforts to probabilistic-based approaches for assessing the collapse of structures under dynamics seismic loadings [25–38], it is worthwhile mentioning that these efforts are aimed at the evaluation of the mean annual frequency of exceeding the limit state corresponding to different performance levels [27,30]. In particular, FEMA P695 is devoted to the quantification of the building seismic performance factors by properly including the different sources of uncertainties [28]. Conversely, the work herein presented is not aimed to such performance assessment, but to the control of the collapse mechanism typology. For this reason, the use of a static approach is justified considering that the control of the collapse mechanism typology can be based on the kinematic theorem of plastic collapse as described in Section 3. The accuracy of such approach is testified by past works on deterministic TPMC [5,11] where the attainment of a collapse mechanism of global type was successively validated using incremental dynamic non-linear analyses.