DAMAGE CONTROLLED DESIGN OF STEEL FRAMES USING STATIC INELASTIC ANALYSIS

George S. Kamaris
Post-Graduate Student
Department of Civil Engineering, University of Patras
Patras, Greece
e-mail: kamaris@upatras.gr

George D Hatzigeorgiou
Lecturer
Department of Environmental Engineering, Democritus University of Thrace
Xanthi, Greece
e-mail: gchatzig@env.duth.gr

Dimitri E. Beskos
Professor
Department of Civil Engineering, University of Patras
Patras, Greece
e-mail: d.e.beskos@upatras.gr

1. ABSTRACT

A direct damage controlled design method of plane steel frames under static loading is proposed. This method is capable of directly managing damage control, both at local and global level, by incorporating in the analysis continuum damage mechanics concepts and equations for ductile materials. The design process is accomplished with the aid of a two-dimensional finite element analysis involving material and geometric nonlinearities. Using the proposed method one can either determine damage for a given structure and loading, or dimension a structure for a target damage and given loading, or determine the maximum loading for a given structure and a target damage level. An example serves to demonstrate the advantages of the method.

2. INTRODUCTION

In this paper, the Direct Damage Controlled Design (DDCD) method, a new design method recently proposed by Hatzigeorgiou and Beskos [1] for concrete structures, is extended here to structural steel design. The DDCD is accomplished with the aid of the two-dimensional (2-D) finite element program DRAIN-2DX [2] which takes into account both material (inelasticity) and geometric (P-δ and P-Δ effects) nonlinearities.The basic advantage of DDCD is the dimensioning of beam members or whole framed structures with damage, directly controlled at both local and global levels. In other words, the designer can select a priori the desired level of damage in a structural member or a whole structure and direct his design in order to achieve this pre-selected level of damage. Furthermore, the preselected level of damage, as it is the case with DDCD, ensures a controlled safety level, not only in strength but also in deflection terms. Thus, the present work, unlike all previous works on damage of steel structures, develops for the first time a direct damage controlled steel design method, which is not just restricted to damage determination as additional structural design information. Table 1 provides the three performance levels (I.O. = Immediate Occupancy, L.S. = Life Safety and C.P. = Collapse Prevention) associated with modern performance-based seismic design with the corresponding limit response values (performance objectives) in terms of IDR = Interstorey Drifts, θ_{pl} = plastic rotation at member end, μ_θ = local ductility and damage..

Performance Levels	IDR	θpl	μ_θ	D
I.O.	1-2% Leelataviwat et al. [3] 1.5% SEAOC [4] 0.5% Vasilopoulos et al. [5] 0.7 % transient negligible permanent FEMA-273 [6]	$\leq\theta_y$ (FEMA273)[6]	2 (FEMA273)[6]	≤5% Vasilopoulos et al.[5] 0.1-10% ATC13[7]
L.S.	2-3% Leelataviwat et al. [3] 3.2 % SEAOC [4] 1.5% Vasilopoulos et al. [5] 2.5 % transient 1% permanent FEMA-273[6]	$\leq 6\theta_y$ (FEMA273)[6]	7 (FEMA273)[6]	≤20% Vasilopoulos et al.[5] 10-30% ATC13[7]
C.P.	3-4% Leelataviwat et al. [3] 3.8%SEAOC [4] 3% Vasilopoulos et al.[5] 5 % transient 5% permanent FEMA-273[6]	$\leq 8\theta_y$ (FEMA273)[6]	9 (FEMA273)[6]	≤50% Vasilopoulos et al.[5] 30-60% ATC13[7]

Table 1.

3. STRESS-STRAIN RELATIONS FOR STEEL

In this work, a multi-linear stress-strain relation for steel characterized by a good compromise between simplicity and accuracy and a compatibility with experimental results is adopted. The stress-strain (σ, ε) relation in tension for this steel model is of the form

$$\begin{aligned} &\sigma = \mathrm{E}\varepsilon && & &\varepsilon \le \varepsilon_y \\ &\sigma = \sigma_y + \mathrm{E}_h(\varepsilon - \varepsilon_y) && \text{for} & &\varepsilon_y < \varepsilon \le \varepsilon_u \\ &\sigma = \sigma_u && & &\varepsilon_u < \varepsilon \end{aligned} \tag{1}$$

where the subscripts y and u stand for yielding and ultimate, respectively. Eq. (1) describes a tri-linear stress-strain relation representing elastoplastic behavior with hardening, with E and E_h indicating the elastic and hardening moduli, respectively.

4. LOCAL DAMAGE

Local damage is usually referred to a point or a part of a structure and is one of the most appropriate indicators about their loading capacity. This paper defines and computes local damage point-wise on the basis of damage mechanics principles. Thus the material degradation process is governed by a damage variable d, the damage index, which is defined as (Lemaitre [8]):

$$d = \lim_{S_n \to 0} \frac{S_n - \bar{S}_n}{S_n} \tag{2}$$

where S_n stands for the overall section in a damage material volume, $\overline{S}_n$ for the effective or undamaged area, while (S_n-$\overline{S}_n$) denotes the inactive area of defects, cracks and voids. Index d becomes 0when the material is undamaged and 1 when it has failed.

The main goal of continuum damage mechanics is the determination of initation and evolution of the damage index d during the deformation process. Lemaitre [8] has proposed a simple damage evolution law, which can successfully simulate the behavior of steel or other ductile materials. This damage evolution law reads

$$\begin{aligned} &d = 0 && & &\varepsilon \le \varepsilon_y \\ &d = \frac{\varepsilon - \varepsilon_y}{\varepsilon_u - \varepsilon_y} && \text{for} & &\varepsilon_y < \varepsilon \le \varepsilon_u \end{aligned} \tag{3}$$

5. GLOBAL DAMAGE AND GLOBAL DAMAGE LEVELS

Global damage is referred to a section of a member, a member, a substructure (e.g. building storey) or a whole structure and constitutes one of the most suitable indicators about their loading capacity.

In this work, the section damage index D_s can be computed as

$$D_S = \frac{c}{d} = \frac{\sqrt{(M_S - M_A)^2 + (N_S - N_A)^2}}{\sqrt{(M_B - M_A)^2 + (N_B - N_A)^2}} \tag{4}$$

where the bending moments M_A, M_S and M_B and the axial forces N_A, N_S and N_B as well as the distances c and d are those shown in the moment M – axial force N interaction diagram of Fig. 1 for a two-dimensional beam-column element. The bending moment M_S and axial force N_S are design loads since the appropriate load factors have been taken into account to have compatibility with EC3 [9]. Fig. 1 includes a lower bound damage curve, the limit between elastic and inelastic material behavior and an upper bound damage curve, the limit between inelastic behavior and complete failure. Thus, damage at the former curve is zero, while at the latter curve is one. Eq. (4) is based on the assumption that damage evolution varies linearly between the above two damage bounds. These lower and upper bound curves can be determined approximately by code type of formulae. Thus, the lower bound can be given by

$$\frac{M}{M_y} + \frac{N}{N_y} = 1 \tag{5}$$

where N_y and M_y are the minimum axial force and bending moment, respectively, which cause inelastic behavior, for instance, at the external fiber, while the upper bound can be given by

$$\frac{M}{M_u} + \left(\frac{N}{N_u}\right)^2 = 1 \tag{6}$$

where N_u and M_u are the ultimate axial force and bending moment, respectively, which cause failure of the section. Eq. (5) and (6) can been used for the construction of the bounding curves of Fig. 1. Since EC3 [9] allows inelastic behavior only for section classes 1 and 2, the proposed method is limited to those section classes in order to have compatibility with it.

In this paper, the member damage index D_M is taken as the largest section damage index, along the member.

For damage assessment of actual structures, however, this approach needs to be extended to multi-member systems. Thus, for a structure composed of m-members, the simplest relation for the overall damage index, D_O, is given by

$$D_O = \left(\frac{\sum_{i=1}^{m} D_{M,i}^2 \Omega_i}{\sum_{i=1}^{m} \Omega_i} \right)^{1/2} \tag{10}$$

where Ω_i denote the volume of the i^{th} member. This relation reflects both the severity of the member damage and the geometric distribution of damage within the structure.

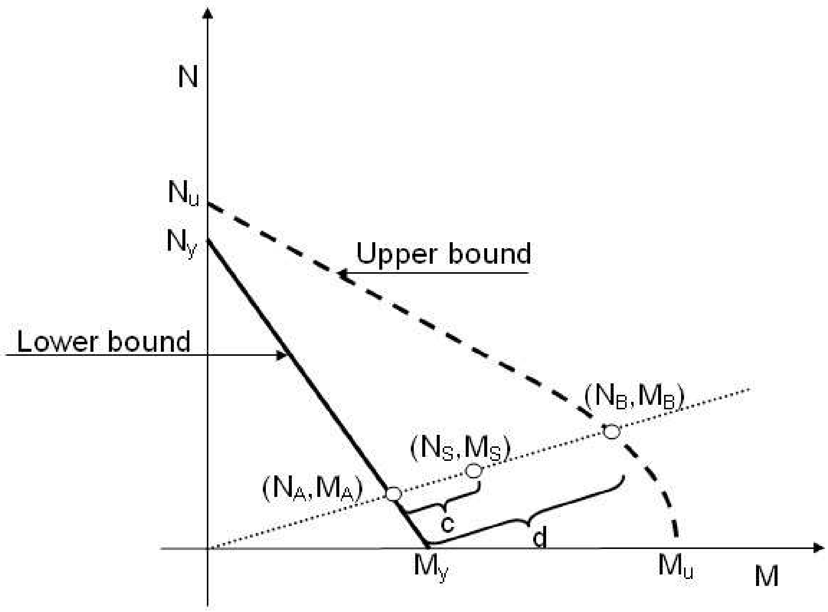

Fig. 1: Definition of damage index D_s

6. DIRECT DAMAGE CONTROLLED STEEL DESIGN

The application of the proposed Direct Damage Controlled Design (DDCD) method to steel members and framed steel structures is done with the aid of the DRAIN-2DX computer program which is based on the finite element method. This program can statically analyze two-dimensional beam structures taking into account material and geometric nonlinearities. Material nonlinearities are accounted for through the fiber modeling of lumped plasticity. Geometric nonlinearities include the P-δ effect and the P-Δ effect are accounted for by utilizing the geometric stiffness matrix.

Using DRAIN-2DX, the user has three design options at his disposal in connection with damage controlled steel design:

a) determine damage for a given structure under given loading
b) dimension a structure for given loading and given target damage
c) determine the maximum loading a given structure can sustain for a given target damage.

7. EXAMPLE OF APPLICATION

A two-dimensional one bay – one storey steel frame is examined in this example. Fig. 2 shows the geometry of the frame. Columns consist of standard HEB sections and beams of standard IPE sections. The frame is subjected to uniform loads 1.35G+1.5Q=30kN/m and a horizontal load 1.35W, where G, Q and W correspond to dead, live and wind loads respectively. The material properties are taken from structural steel grade S235 divided by a factor 1.10 for compatibility with EC3[9].

In the following, the frame is examined for the first and second design options. Initially, the design option, related to the determination of damage for a given structure and known loading, is examined. Columns consist of HEB240 sections and beams of IPE330 sections. The vertical loads remain constant and the horizontal load is increased incrementally during the inelastic static analysis until collapse. The results for damage, plastic rotation and local ductility μ_θ of the frame at the three performance levels of FEMA-273[6] defined by IDR are presented in Table 2.

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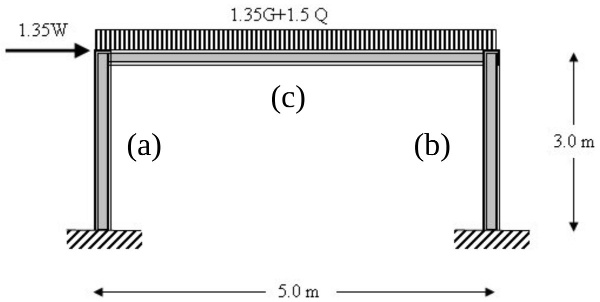

Fig. 2: Frame considered in the example

The second design option has to do with member dimensioning for a pre-selected damage level and known loading. In this case the vertical loading is 1.35G+1.5Q=30kN/m, as previously and the wind load equals to 1.35W= 229.65kN. The maximum member damage is set equal to 0% and 20% for columns and beams respectively. The appropriate sections in this case appear to be HEB260 for columns and IPE330 for beams

Member	Perfomance Level	Damage (%)	θ_{pl}		μ_θ
(a)	I.O.	4.3	end i	0	1
			end j	0	1
	L.S.	31.14	end i	$2.2\theta_y$	3.2
			end j	0	1
	C.P.	53.55	end i	$5.35\theta_y$	6.35
			end j	0	1
(b)	I.O.	19.23	end i	$0.17\theta_y$	1.17
			end j	0	1
	L.S.	35.58	end i	$2.35\theta_y$	3.35
			end j	0	1
	C.P.	56.69	end i	$5.50\theta_y$	6.5
			end j	$1.40\theta_y$	2.4
(c)	I.O.	15.45	end i	0	1
			end j	$0.2\theta_y$	1.2
	L.S.	31.71	end i	$1.44\theta_y$	2.44
			end j	$3.06\theta_y$	4.06
	C.P.	50.4	end i	$4.4\theta_y$	5.4
			end j	$5.62\theta_y$	6.62

Table 3**.**

8. CONCLUSIONS

In this work, the theoretical principles and the computational procedures of the Direct Damage Controlled Method (DDCD) for the static design of plane framed steel structures were presented. The proposed methodology quantifies and controls damage in a direct and transparent manner much better than any of the existing methods of structural design. More specifically, with this method the designer can either determine the damage level for a given structure and known loading, or dimension a structure for a target damage level and known loading, or determine the maximum loading for a given structure and a target damage level.

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ΣΧΕΔΙΑΣΜΟΣ ΜΕΤΑΛΛΙΚΩΝ ΠΛΑΙΣΙΩΝ ΜΕ ΑΜΕΣΟ ΕΛΕΓΧΟ ΤΗΣ ΒΛΑΒΗΣ ΜΕ ΧΡΗΣΗ ΣΤΑΤΙΚΗΣ ΑΝΕΛΑΣΤΙΚΗΣ ΑΝΑΛΥΣΗΣ

Γεώργιος Σ. Καμάρης
Μεταπτυχιακός φοιτητής
Πανεπιστήμιο Πατρών
Πάτρα, Ελλάδα
e-mail: kamaris@upatras.gr

Γεώργιος Δ. Χατζηγεωργίου
Λέκτωρας
Δημοκρίτειο Πανεπιστήμιο Θράκης
Ξάνθη, Ελλάδα
e-mail gchatzig@env.duth.gr

Δημήτριος Ε. Μπέσκος
Καθηγητής
Πανεπιστήμιο Πατρών
Πάτρα, Ελλάδα
e-mail: d.e.beskos@upatras.gr

1. ΠΕΡΙΛΗΨΗ

Παρουσιάζεται μία νέα μέθοδος σχεδιασμού μεταλλικών επίπεδων πλαισιωτών κατασκευών υπό στατική φόρτιση, η οποία έχει την ικανότητα να ελέγχει άμεσα τη βλάβη. Η μέθοδος αυτή είναι ικανή να επιτυγχάνει άμεσο έλεγχο της βλάβης, τόσο σε τοπικό όσο και καθολικό επίπεδο, με τη βοήθεια της θεωρίας βλάβης του συνεχούς μέσου για όλκιμα υλικά. Η διαδικασία σχεδιασμού επιτυγχάνεται με τη βοήθεια ενός προγράμματος πεπερασμένων στοιχείων που λαμβάνει υπόψη του μη γραμμικότητες υλικού και γεωμετρικές μη γραμμικότητες. Με τη χρήση της μεθόδου, δίνονται τρεις επιλογές για το σχεδιασμό μεταλλικών κατασκευών, οι οποίες είναι: 1) Ο προσδιορισμός της βλάβης συγκεκριμένης κατασκευής με δεδομένο φορτίο. 2) Η διαστασιολόγηση μίας κατασκευής για δεδομένο φορτίο και συγκεκριμένη επιθυμητή βλάβη. 3) Ο προσδιορισμός του μέγιστου φορτίου που μπορεί να αντέξει μία δεδομένη κατασκευή με συγκεκριμένη επιθυμητή βλάβη.