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Development of the large increment method for elastic perfectly plastic analysis of plane frame structures under monotonic loading

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Abstract

The displacement-based finite element method dominates current practice for material nonlinear analysis of structures. However, there are several characteristics that may limit the effectiveness of this approach. In particular, for elastoplastic analysis, the displacement method relies upon a step-by-step incremental approach stemming from flow theory and also requires significant mesh refinement to resolve behavior in plastic zones. This leads to computational inefficiencies that, in turn, encourage the reconsideration of force-based approaches for elastoplastic problems.

One of these force algorithms that has been recently developed is the large increment method. The main advantage of the flexibility-based large increment method (LIM) over the displacement method is that it separates the global equilibrium and compatibility equations from the local constitutive relations. Consequently, LIM can reach the solution in one large increment or in a few large steps, thus, avoiding the development of cumulative errors. This paper discusses the extension of the large increment methodology for the nonlinear analysis of plane frame structures controlled by an elastic, perfectly plastic material model. The discussion focuses on the power of LIM to handle these nonlinear problems, especially when plastic hinges form in the frame and ultimately as the structure approaches the collapse stage. Illustrative planar frame examples are presented and the results are compared with those obtained from a standard displacement method.

Keywords: Planar frames; Monotonic loading; Nonlinear analysis; Displacement method; Force method; Large increment method (LIM); Elastic-perfectly plastic material model; Generalized inverse

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Nomenclature

B	strain–displacement matrix
C^{e}	element equilibrium matrix
C	equilibrium matrix of structure
C_R^{-1}	generalized inverse of matrix C
D	generalized nodal displacement
F	generalized inner force vector of whole system
I	identity matrix
M_{p}	maximum fully plastic moment of the section
M_{y}	fully elastic moment of the section
N_{p}	maximum fully plastic normal force of the section
N_{y}	fully elastic normal force of the section
P	generalized node load vector
Q	nodal displacement shape function
S	vector of search direction
X	arbitrary vector of dimension n
Z	stress shape function
b	beam cross-sectional width
$\hat{b}$	body force vector
d	nodal displacement variable
$e(\delta_n)$	error criteria for compatibility condition at iteration n
f	generalized force variable
f_{e_i}	element forces of element i
h	beam cross-sectional height
h_n	multiplier along the search direction S_n
l	degree of indeterminacy
m	dimension of the generalized nodal displacement vector
n	dimension of the generalized inner force vector of whole system
q	total number of elements ends
r	number of element rigidity
$\hat{t}$	external traction vector
Θ	eigenvectors
$K'(\delta)$	current stiffness matrix for the whole system
$\Phi'(\delta)$	current flexibility stiffness matrix for the whole system
χ_{p}	cross-sectional fraction at the yield stress
α	$n \times n$ matrix related to C
β	$n \times n$ matrix related to C
δ	generalized deformation vector for whole system
δ_{e_i}	deformation variables of element i
δ^{p}	plastic deformation
ε	strain tensor
ε^{p}	plastic strain tensor
ρ	number of elements
η	variable index
θ_{p}	plastic hinge rotation