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# Civil engineering applications of the Asymptotic Expansion Load Decomposition beam model, an overview

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**Abstract** The Asymptotic Expansion Load Decomposition higher-order beam model is based on the classical two-scale asymptotic expansion in the linear elasticity framework. It was successively extended to eigenstrains and to plasticity in small deformations in different papers. The present paper offers a comprehensive and consistent presentation of our approach applied to civil engineering applications.

**Keywords** Model reduction; Higher-order beam model; Asymptotic expansion; Plasticity; Structural analysis

## 1 Introduction

Until very recently, most structural engineering offices were designing structures based either on very simple beam models or on complex finite elements modeling. Thanks to the recent development of cloud-computing, a new business model is emerging: online structural analysis. Indeed, cloud computing gives structural engineers access to more powerful computing platforms. It also reduces maintenance operations for the provider since only one system is maintained instead of adapting the software to multiple platforms (Windows, Unix, multiple versions of them, etc.). This is the path chosen by the start-up *Strains engineering* co-founded by Xavier Cespedes in 2014.

The development of such tools requires interactive and real-time simulation softwares. Hence, an efficient mechanical modeling of structural elements and connections is critical. One of the main project of this start-up is the development of a higher-order beam model capable of capturing in more details the influence of the applied load or the boundary conditions for thin-walled and heterogeneous beams. Indeed, traditional design based on simple beam modeling presents the advantage to be easy to understand and to allow rapid

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29 verification of the results. However, it is not able to give detailed information about local  
30 distribution of stresses. In order to obtain more detailed results, complex finite element  
31 modeling is necessary. Though, this requires expensive and black-boxed software and is  
32 computationally more demanding.

33 The present paper summarizes and presents a critical review of the Asymptotic Expansion  
34 Load Decomposition beam model developed and implemented for *Strains engineering* and  
35 published in several contributions [13, 9, 10]. This model originates from the seminal work  
36 of Miara and Trabucho [19] for linear elastic beams and was first directly applied by Ferradi  
37 et al [13]. Because structural analysis must also take into account eigenstrains such as thermal  
38 load, prestress or weakly coupled swelling phenomena, this new type of loading was treated  
39 by Corre et al [9] in a linear elastic framework. Finally, since the total plastic strain may  
40 be considered as an eigenstrain, the Asymptotic Expansion Load Decomposition model was  
41 extended to elasto-plasticity assuming small perturbations in [10].

42 The paper is organized in two sections. First, the higher-order beam model is derived in the  
43 framework of linear elasticity for a given load distribution and some illustrations are briefly  
44 presented. Second, the higher-order beam model is extended to elasto-plasticity assuming  
45 small perturbations and is validated against a full 3D computation. Finally, limitations and  
46 outlooks of the approach are presented.

## 47 **2 The linear elastic Asymptotic Expansion Load Decomposition beam model**

48 Most beam models are based on *ad-hoc* assumptions on the 3D fields which motivated the  
49 denomination *axiomatic*. They rely on an educated guess on the 3D displacement field in  
50 a separated form between the longitudinal coordinate and the transverse coordinates. Then,  
51 straightforward application of the minimum of potential energy leads to 1D boundary value  
52 problems corresponding to the beam model.

53 Numerous strategies were devised for building the kinematics of the beam. Remarkably,  
54 the extended Saint Venant solution from Iesan [15] and the formal asymptotic expansion  
55 method [29] delivers almost the same collection of cross-section displacements. Based on  
56 the seminal idea from Vogelius and Babuška [30, 31] which also originated the family of  
57 “hierarchical models” for plates and shells [1], Miara and Trabucho [19] made two noticeable  
58 observations regarding this beam kinematics. First, the formal asymptotic expansion delivers  
59 a free family of kinematic enrichment which is dense in the space of the 3D solution. This  
60 means that going sufficiently high in the expansion allows arbitrary refinement of the 3D  
61 solution. Second, the truncation of this family ensures that the corresponding beam model  
62 is asymptotically consistent except at the boundary. Indeed, for loads which do not generate  
63 boundary layers, Miara and Trabucho [19] proved a higher-order convergence result. This  
64 means that the kinematic enrichment delivered by the formal asymptotic expansion is optimal  
65 in terms of approximation error far from the extremities of the beam.

66 In the following, the asymptotic expansion procedure for deriving the AELD kinematics  
67 is recalled for a beam under body loads and its link with classical beam models is highlighted.  
68 Then, the higher-order beam model is derived and two applications are presented.

### 69 **2.1 The kinematic enrichment based on the formal asymptotic expansion**

70 In this section, the formal asymptotic expansion procedure is recalled for a linear elastic  
71 beam loaded by an arbitrary body force. It is an opportunity to emphasize its close link with

72 Saint-Venant solution as well as the extension from Iesan [15]. It appears that a series of  
 73 3D displacement fields distributed over the cross-section may be obtained as function of  
 74 the classical beam generalized displacements as well as the longitudinal distribution of the  
 75 applied load and its higher gradients. Such a basis of “sections modes” may be derived for  
 76 any given applied load [13] and was extended to prescribed eigenstrains by Corre et al [9].

### 77 2.1.1 The 3D problem

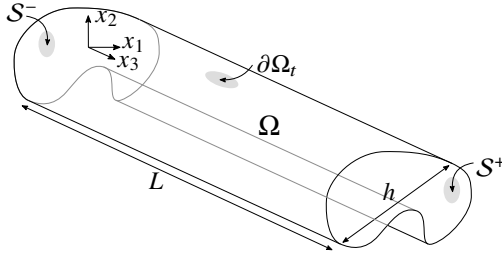


Fig. 1: The beam 3D configuration

78 We consider a beam occupying the prismatic domain  $\Omega$  (Figure 1) with a length  $L$  and  
 79 a cross-sectional typical size  $h$ . The boundary  $\partial\Omega$  is the union of the lateral (free) surface  
 80  $\partial\Omega_t$  and the two end sections  $S^\pm$  (clamped). The longitudinal coordinate is  $x_3$  and the  
 81 transverse coordinates are  $x_1$  and  $x_2$  denoted as  $x_\alpha$ , the corresponding reference frame is  
 82 denoted  $(O, \underline{e}_1, \underline{e}_2, \underline{e}_3)$  where  $O$  is an arbitrary point of the plane  $x_3 = 0$ .

83 The constitutive material of the beam, relating the stress tensor  $\sigma$  to the linearized deformation  $\varepsilon$ , is only function of the transverse coordinates  $x_\alpha$  and invariant in the longitudinal direction. For convenience and without limitation, the corresponding fourth order stiffness tensor  $C(x_\alpha)$  is assumed monoclinic with respect to a plane of normal  $\underline{e}_3$ :

$$C_{\alpha\beta\gamma 3} = C_{333\alpha} = 0. \quad (1)$$

87 The beam is only subjected to a body load  $f_i$ . The corresponding 3D linear boundary value  
 88 problem writes as:

$$\begin{cases} \mathbf{div}(\sigma) + \underline{f} = 0 & \text{on } \Omega, \\ \sigma = C : \varepsilon(\underline{u}) & \text{on } \Omega, \\ \sigma \cdot \underline{n} = 0 & \text{on } \partial\Omega_t, \\ \underline{u} = 0 & \text{on } S^\pm, \end{cases} \quad (2)$$

89 where  $\underline{n}$  is the outer normal to  $\partial\Omega_t$ ,  $\mathbf{div}$  is the classical divergence operator and  $\varepsilon(\underline{u})$  is the  
 90 symmetric part of the displacement gradient.

91 *Scaling and variable separation* A new set of coordinates  $y_i$  is defined from the global  
 92 coordinates,

$$(x_1, x_2, x_3) = (hy_1, hy_2, Ly_3), \quad (3)$$

93 which rewrites the derivation operator as:

$$\nabla_{\underline{x}} = \frac{1}{L} \left( \nabla_{y_3} + \frac{1}{h} \nabla_{y_\alpha} \right), \quad (4)$$

94 as well as the integration over the domain  $\Omega$  as:

$$\int_{\Omega} d\Omega = \int_0^L \int_S dx_{\alpha} dx_3 = L^3 \eta^2 \int_0^1 \int_{S^0} dy_{\alpha} dy_3 = L^3 \eta^2 \int_0^1 \langle \rangle dy_3, \quad (5)$$

95 where  $\eta = \frac{h}{L}$  is the small parameter related to the slenderness of the beam,  $S^0$  is the scaled  
96 cross-section, independent from  $\eta$  and  $\langle \rangle$  denotes integration on the scaled cross-section.

97 The body load is assumed to have the following separated form:

$$f_{\alpha} = \frac{\eta^2}{L} \tilde{f}_{\alpha}(y_{\eta}) F(y_3) \quad \text{and} \quad f_3 = \frac{\eta}{L} \tilde{f}_3(y_{\eta}) F(y_3) \quad (6)$$

98 where  $\tilde{f}_i$  are cross-section distributions of the load which are modulated by a single longitu-  
99 dinal function  $F(x_3)$ . In this section, capital letters denote functions of only the  $y_3$  coordinate  
100 (except for  $C$ ) and  $\tilde{\bullet}$  denotes functions of only cross-section coordinates  $y_{\alpha}$ .

101 *Expansion* The asymptotic expansion method is a formal procedure in which all fields are  
102 assumed sufficiently smooth. It yields a cascade of cross-section and longitudinal boundary  
103 value problems which are classically solved recursively. In the present case, only the cross-  
104 section problems are of interest in order to derive a collection of displacement modes.

105 The displacement, strain and stress variables are expanded as power series of the small  
106 parameter as follows [24, 29, 6]:

$$\mathbf{u} = L \left( U_{\alpha}^0(y_3) \mathbf{e}_{\alpha} + \eta \mathbf{u}^1 + \eta^2 \mathbf{u}^2 + \dots \right), \quad (7)$$

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^0 + \eta \boldsymbol{\varepsilon}^1 + \eta^2 \boldsymbol{\varepsilon}^2 + \dots, \quad (8)$$

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}^0 + \eta \boldsymbol{\sigma}^1 + \eta^2 \boldsymbol{\sigma}^2 + \dots \quad (9)$$

109 and introduced in the rescaled equations of the 3D boundary value problem (2) where each  
110 power  $p$  of  $\eta$  is identified. In Equation 7, Einstein's implicite summation convention on  
111 repeated indices is used. Note that, Greek indices denotes transverse dimensions:  $\alpha, \beta \dots =$   
112 1, 2 and Latin indices denotes all three dimensions:  $i, j \dots = 1, 2, 3$ .

113 The problem being linear, the choice of the starting order has no incidence on the final  
114 formulation in terms of physical variable. Here the starting order is chosen so that the leading  
115 order of the displacement field is 0. The starting order of the other fields is chosen accordingly  
116 and motivates the scaling of the load in Equation (6).

117 For  $p \in \mathbb{N}$ , each compatibility equations, boundary conditions and constitutive equations  
118 for  $p$  and equilibrium equations for  $p - 1$  yield an auxiliary problem on the cross-section  
119 which splits in two uncoupled boundary value problems.

*Transverse displacement* First, the cross-section displacement problems (transverse mode)  
 $\mathcal{T}^{p+1}$  are gathered for  $p \geq 0$ :

$$\mathcal{T}^{p+1} : \begin{cases} \sigma_{\alpha\beta,\beta}^p + \sigma_{\alpha 3,3}^{p-1} + \delta_{p3} \tilde{f}_{\alpha} F = 0 & \text{on } \mathcal{S}^0, & (10a) \\ \sigma_{\alpha\beta}^p = C_{\alpha\beta\gamma\delta} \varepsilon_{\delta\gamma}^p + C_{\alpha\beta 33} \varepsilon_{33}^p & \text{on } \mathcal{S}^0, & (10b) \\ \sigma_{33}^p = C_{33\alpha\beta} \varepsilon_{\beta\alpha}^p + C_{3333} \varepsilon_{33}^p & \text{on } \mathcal{S}^0, & (10c) \\ \varepsilon_{\alpha\beta}^p = u_{(\alpha,\beta)}^{p+1}, \quad \varepsilon_{33}^p = u_{3,3}^p & \text{on } \mathcal{S}^0, & (10d) \\ \sigma_{\alpha\beta}^p n_{\beta} = 0 & \text{on } \partial\mathcal{S}^0. & (10e) \end{cases}$$

120 where  $\sigma^{-1} = 0$  and  $\delta_{3p} = 1$  if  $p = 3$  and  $\delta_{3p} = 0$  else. Transposing the results from [8, 2],  
 121 for a simply connected cross-section and regular enough  $C$  and loadings, this boundary value  
 122 problem on the displacement  $u_\alpha^{p+1}$  is a pure traction (Neumann) problem which is well-posed  
 123 provided that the applied load is globally self-equilibrating for cross-section translations and  
 124 rotation:

$$\left\langle \sigma_{\alpha 3,3}^{p-1} + \delta_{p3} \tilde{f}_\alpha F \right\rangle = 0 \quad \text{and} \quad \left\langle y_\beta \epsilon_{\beta\alpha} \left( \sigma_{\alpha 3,3}^{p-1} + \delta_{p3} \tilde{f}_\alpha F \right) \right\rangle = 0, \quad (11)$$

125 where  $\epsilon_{\alpha\beta}$  is the permutation operator:  $\epsilon_{11} = \epsilon_{22} = 0$ ,  $\epsilon_{12} = +1$ ,  $\epsilon_{21} = -1$ . Then, under  
 126 compatibility conditions (11), the solution is uniquely defined up to the following rigid  
 127 motion of the section in its plane:

$$u_\alpha^{R,p+1} = U_\alpha^{p+1}(y_3) + y_\beta \epsilon_{\beta\alpha} \Theta^{p+1}(y_3). \quad (12)$$

128 where  $U_\alpha^{p+1}$  is a transverse displacement and  $\Theta^{p+1}$  a twist rotation.

*Longitudinal displacement* Second, the longitudinal displacement problems (warping mode)  
 $\mathcal{W}^p$  are obtained for  $p \geq 0$ :

$$\mathcal{W}^{p+1} : \begin{cases} \sigma_{3\alpha,\alpha}^p + \sigma_{33,3}^{p-1} + \delta_{p2} \tilde{f}_3 F = 0 & \text{on } S^0, & (13a) \\ \sigma_{\alpha 3}^p = C_{\alpha 3\beta 3} 2\epsilon_{\beta 3}^p & \text{on } S^0, & (13b) \\ 2\epsilon_{\alpha 3}^p = u_{3,\alpha}^{p+1} + u_{\alpha,3}^p & \text{on } S^0, & (13c) \\ \sigma_{\alpha 3}^p n_\alpha = 0 & \text{on } \partial S^0. & (13d) \end{cases}$$

129 Again, for a simply connected cross-section and regular enough  $C$  and loadings, this bound-  
 130 ary value problem on the displacement  $u_3^{p+1}$  is well-posed if the applied load is globally  
 131 self-equilibrating for the longitudinal translation:

$$\left\langle \sigma_{33,3}^{p-1} + \delta_{p2} \tilde{f}_3 F \right\rangle = 0. \quad (14)$$

132 In this case, the solution is uniquely defined up to a uniform longitudinal displacement:

$$u_3^{R,p+1} = U_3^{p+1}(y_3). \quad (15)$$

133 *Resultants and macroscopic equilibrium equations* The rigid motion of the section suggests  
 134 the following definition of the beam resultants at each order  $p \geq 0$ :

$$N_3^p = \langle \sigma_{33}^p \rangle, \quad M_\alpha^p = \langle y_\alpha \sigma_{33}^p \rangle, \quad M_3^p = \langle y_\beta \epsilon_{\beta\alpha} \sigma_{\alpha 3}^p \rangle \quad \text{and} \quad V_\alpha^p = \langle \sigma_{\alpha 3}^p \rangle, \quad (16)$$

135 where  $N_3^p$  is the normal traction,  $M_\alpha^p$  are the bending moments<sup>1</sup>,  $M_3^p$  is the moment of torsion  
 136 and  $V_\alpha^p$  are the shear forces.

From the compatibility conditions (10a) and (13a) it is possible to prove that these  
 resultants must comply with the following classical beam equilibrium equations for each  
 $p \geq 0$ :

$$\begin{cases} N_{3,3}^p + \delta_{p1} p_3 F = 0, & (17a) \\ M_{\alpha,3}^p - V_\alpha^{p+1} + \delta_{p1} \mu_\alpha F = 0, & (17b) \\ M_{3,3}^p + \delta_{p2} \mu_3 F = 0, & (17c) \\ V_{\alpha,3}^p + \delta_{p2} p_\alpha F = 0. & (17d) \end{cases}$$

<sup>1</sup> It will appear that  $M_\alpha^p$  is the working conjugate to the curvature  $U_{\alpha,33}^p$  and not the conventional  
 bending moment. Indeed, the classical definition is  $m_\alpha^p = \langle \epsilon_{\alpha\beta} y_\beta \sigma_{33}^p \rangle = \epsilon_{\alpha\beta} M_\beta^p$ . This choice is made for  
 convenience.

137 where  $p_\alpha = \langle \tilde{f}_\alpha \rangle$  are the transverse loads,  $p_3 = \langle \tilde{f}_3 \rangle$  is the longitudinal load,  $\mu_\alpha = \langle y_\alpha \tilde{f}_3 \rangle$   
 138 are distributed bending couples and  $\mu_3 = \langle y_\beta \epsilon_{\beta\alpha} \tilde{f}_\alpha \rangle$  is a distributed torsion load.

139 The series of problems are now solved order by order.

### 140 2.1.2 First-order problems

141 *Transverse displacement* The problem  $\mathcal{T}^1$  is not loaded. Consequently, the transverse dis-  
 142 placement  $u_\alpha^1$  is a rigid motion and the corresponding stress is null:

$$u_\alpha^1 = U_\alpha^1(y_3) + y_\beta \epsilon_{\beta\alpha} \Theta^1(y_3) \quad \text{and} \quad \sigma_{\alpha\beta}^0 = 0, \quad \sigma_{33}^0 = 0. \quad (18)$$

143 Here,  $\Theta^1$  appears as the leading order angle of twist and  $U_\alpha^1$  as the second order macroscopic  
 144 transverse displacement.

*Longitudinal displacement* The longitudinal displacement problem (warping mode)  $\mathcal{W}^1$   
 writes as:

$$\mathcal{W}^1 : \begin{cases} \sigma_{3\alpha,\alpha}^0 = 0 & \text{on } \mathcal{S}^0, & (19a) \\ \sigma_{\alpha 3}^0 = C_{\alpha 3\beta 3} 2\varepsilon_{\beta 3}^0 & \text{on } \mathcal{S}^0, & (19b) \\ 2\varepsilon_{\alpha 3}^0 = u_{3,\alpha}^1 + U_{\alpha,3}^0 & \text{on } \mathcal{S}^0, & (19c) \\ \sigma_{\alpha 3}^0 n_\alpha = 0 & \text{on } \partial\mathcal{S}^0. & (19d) \end{cases}$$

145 The applied load is self-equilibrating and the solution of this boundary value problem writes  
 146 as:

$$u_3^1 = U_3^1 + y_\alpha U_{\alpha,3}^0 \quad \text{and} \quad \sigma_{\alpha 3}^0 = 0, \quad (20)$$

147 where  $U_{\alpha,3}^0$  appears as the bending rotation and  $U_3^1$  as the leading order longitudinal dis-  
 148 placement.

### 149 2.1.3 Second-order problems

*Transverse displacement* The transverse displacement  $u_\alpha^2$  is derived through:

$$\mathcal{T}^2 : \begin{cases} \sigma_{\alpha\beta,\beta}^1 = 0 & \text{on } \mathcal{S}^0, & (21a) \\ \sigma_{\alpha\beta}^1 = C_{\alpha\beta\gamma\delta} \varepsilon_{\delta\gamma}^1 + C_{\alpha\beta 33} \varepsilon_{33}^1, & \text{on } \mathcal{S}^0, & (21b) \\ \sigma_{33}^1 = C_{33\alpha\beta} \varepsilon_{\beta\alpha}^1 + C_{3333} \varepsilon_{33}^1 & \text{on } \mathcal{S}^0, & (21c) \\ \varepsilon_{\alpha\beta}^1 = u_{(\alpha,\beta)}^2, \quad \varepsilon_{33}^1 = U_{3,3}^1 + y_\alpha U_{\alpha,33}^0 & \text{on } \mathcal{S}^0, & (21d) \\ \sigma_{\alpha\beta}^1 n_\beta = 0 & \text{on } \partial\mathcal{S}^0. & (21e) \end{cases}$$

150 Again, the applied load is globally self-equilibrating. The solution of this boundary value  
 151 problem parametrized by the elongation  $U_{3,3}^1$  and the curvatures  $U_{\alpha,33}^0$  writes as the linear  
 152 superposition of each contribution:

$$u_\alpha^2 = \tilde{u}_\alpha^{\varepsilon^3} U_{3,3}^1 + \tilde{u}_\alpha^{\chi^\beta} U_{\beta,33}^0 + U_\alpha^2 + y_\beta \epsilon_{\beta\alpha} \Theta^2, \quad (22)$$

153 where  $\tilde{u}_\alpha^{\varepsilon^3}$ ,  $\tilde{u}_\alpha^{\chi^\beta}$  are cross-section displacements related to transverse Poisson's effect under  
 154 pure traction and pure curvatures which are illustrated for a square section in Figure 2. When  
 155 the section is homogeneous, these correctors have a closed-form expression which is detailed

156 in [32] for instance. In order to be uniquely defined, the following constraints are applied to  
 157 all these cross-section displacements:

$$\langle \tilde{u}_\alpha \rangle = 0 \quad \text{and} \quad \langle y_\beta \epsilon_{\beta\alpha} \tilde{u}_\alpha \rangle = 0. \quad (23)$$

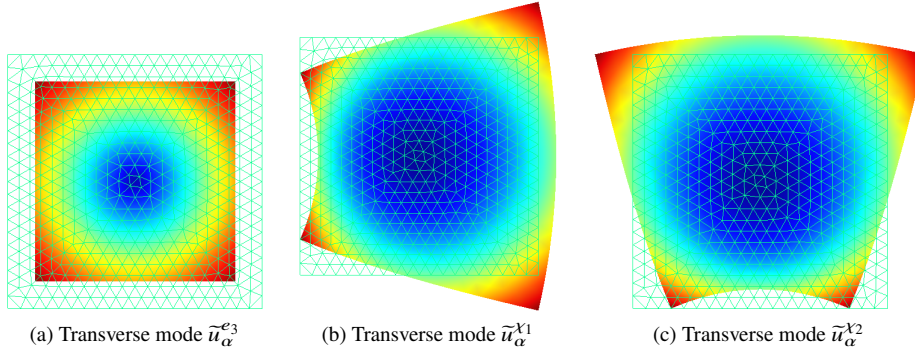


Fig. 2: Transverse modes related to pure traction and pure curvatures for a homogeneous square section with an isotropic material

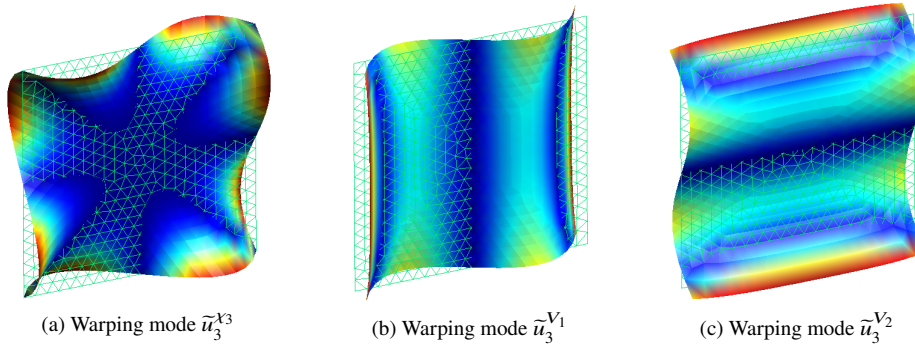


Fig. 3: Warping modes related to pure torsion and pure shear forces for a homogeneous square section with an isotropic material

158

*Longitudinal displacement* The longitudinal displacement  $u_3^2$  complies with:

$$\mathcal{W}^2 : \begin{cases} \sigma_{3\alpha,\alpha}^1 = 0 & \text{on } \mathcal{S}^0, & (24a) \\ \sigma_{\alpha 3}^1 = C_{\alpha 3 \beta 3} 2\epsilon_{\beta 3}^1 & \text{on } \mathcal{S}^0, & (24b) \\ 2\epsilon_{\alpha 3}^1 = u_{3,\alpha}^2 + y_\beta \epsilon_{\beta\alpha} \Theta_{,3}^1 + U_{\alpha,3}^1 & \text{on } \mathcal{S}^0, & (24c) \\ \sigma_{\alpha 3}^1 n_\alpha = 0 & \text{on } \partial\mathcal{S}^0. & (24d) \end{cases}$$



159 The applied load is globally self-equilibrating. The solution of this boundary value problem  
160 parametrized by  $\Theta_{,3}^1$  and  $U_{\alpha,3}^1$  writes as the linear superposition of each contribution:

$$u_3^2 = \tilde{u}_3^{\chi_3} \Theta_{,3}^1 + U_3^2 + y_\alpha U_{\alpha,3}^1, \quad (25)$$

161 where  $\tilde{u}_3^{\chi_3}$  is the torsion warping<sup>2</sup> illustrated in Figure 3a. Indeed, the displacement  $\tilde{u}_3^{\chi_3}$  is  
162 exactly the solution of the Neumann problem for Saint Venant's torsion. Again, this warping  
163 is constrained as follows:

$$\langle \tilde{u}_3 \rangle = 0. \quad (26)$$

*Macroscopic constitutive equations* From the solution of second order problems, the first order stress may be written as:

$$\left\{ \begin{array}{l} \sigma_{\alpha\beta}^1 = \tilde{\sigma}_{\alpha\beta}^{\epsilon_3} U_{3,3}^1 + \tilde{\sigma}_{\alpha\beta}^{\chi_1} U_{1,33}^0 + \tilde{\sigma}_{\alpha\beta}^{\chi_2} U_{2,33}^0, \end{array} \right. \quad (27a)$$

$$\left\{ \begin{array}{l} \sigma_{\alpha 3}^1 = \tilde{\sigma}_{\alpha 3}^{\chi_3} \Theta_{,3}^1, \end{array} \right. \quad (27b)$$

$$\left\{ \begin{array}{l} \sigma_{33}^1 = \tilde{\sigma}_{33}^{\epsilon_3} U_{3,3}^1 + \tilde{\sigma}_{33}^{\chi_1} U_{1,33}^0 + \tilde{\sigma}_{33}^{\chi_2} U_{2,33}^0. \end{array} \right. \quad (27c)$$

Expressing the traction and bending moments leads to the following constitutive equations:

$$\left\{ \begin{array}{l} N_3^1 = A_3 U_{3,3}^1 + S_1 U_{1,33}^0 + S_2 U_{2,33}^0, \end{array} \right. \quad (28a)$$

$$\left\{ \begin{array}{l} M_1^1 = S_1^* U_{3,3}^1 + D_1 U_{1,33}^0 + D_{12} U_{2,33}^0, \end{array} \right. \quad (28b)$$

$$\left\{ \begin{array}{l} M_2^1 = S_2^* U_{3,3}^1 + D_{12}^* U_{1,33}^0 + D_2 U_{2,33}^0, \end{array} \right. \quad (28c)$$

164 where:

$$\left\{ \begin{array}{l} A_3 = \langle \tilde{\sigma}_{33}^{\epsilon_3} \rangle, \quad S_1 = \langle \tilde{\sigma}_{33}^{\chi_1} \rangle, \quad S_2 = \langle \tilde{\sigma}_{33}^{\chi_2} \rangle, \\ S_1^* = \langle y_1 \tilde{\sigma}_{33}^{\epsilon_3} \rangle, \quad D_1 = \langle y_1 \tilde{\sigma}_{33}^{\chi_1} \rangle, \quad D_{12} = \langle y_1 \tilde{\sigma}_{33}^{\chi_2} \rangle, \\ S_2^* = \langle y_2 \tilde{\sigma}_{33}^{\epsilon_3} \rangle, \quad D_{12}^* = \langle y_2 \tilde{\sigma}_{33}^{\chi_1} \rangle, \quad D_2 = \langle y_2 \tilde{\sigma}_{33}^{\chi_2} \rangle. \end{array} \right. \quad (29)$$

The modulus  $A_3$  is the traction stiffness,  $D_1$  and  $D_2$  are the bending stiffnesses. It is possible to prove that  $S_1^* = S_1$ ,  $S_2^* = S_2$  and  $D_{12}^* = D_{12}$ . The stiffnesses  $S_1$  and  $S_2$  are related to the first moments of inertia. Furthermore, there is a position for  $O$ , the origin of the reference frame, such that  $S_1 = S_2 = 0$  and rotating the reference frame with respect to  $\underline{e}_3$ , there is an angle such that  $D_{12} = 0$ . When the section is homogeneous, this choice of reference frame corresponds to the centroid of the section oriented along one of the principal axis of the second moments of inertia. This is assumed in the following:

$$\left\{ \begin{array}{l} N_3^1 = A_3 U_{3,3}^1, \end{array} \right. \quad (30a)$$

$$\left\{ \begin{array}{l} M_1^1 = D_1 U_{1,33}^0, \end{array} \right. \quad (30b)$$

$$\left\{ \begin{array}{l} M_2^1 = D_2 U_{2,33}^0. \end{array} \right. \quad (30c)$$

165 Similarly, the torsion is expressed as function of the macroscopic displacements and the  
166 eigenstrain:

$$M_3^1 = D_3 \Theta_{,3}^1, \quad (31)$$

167 where the torsion stiffness is:

$$D_3 = \langle y_\gamma \epsilon_{\gamma\alpha} \tilde{\sigma}_{\alpha 3}^{\chi_3} \rangle. \quad (32)$$

168 Whereas the uncoupling between traction and bending moments may always be satisfied  
169 with a proper choice of the reference frame, the uncoupling between torsion is obtained here  
170 because of the symmetry assumption (1). This assumption may be released without limiting  
171 the approach presented here. Indeed, constitutive equations (30) and (31) would be simply  
172 coupled in such a case and would make the derivation more involved.

<sup>2</sup>  $\tilde{u}_3^{\chi_3}$  is the warping used by Bencoter [4].

173 *2.1.4 Third-order problems*

174 *Transverse displacement* The transverse displacement  $u_\alpha^3$  is derived through  $\mathcal{T}^3$  and loaded  
 175 by  $\Theta_{,33}^1$ ,  $U_{3,3}^2$  and  $U_{\alpha,33}^1$ . Noticing that the constitutive equation (31) and the torsion equi-  
 176 librium equation (17c) for  $p = 1$ , enforce  $\Theta_{,33}^1 = 0$ , it appears that  $\mathcal{T}^3$  is exactly the same  
 177 problem as  $\mathcal{T}^2$ , incrementing the orders<sup>3</sup>.

178 *Longitudinal displacement* The longitudinal displacement  $u_3^3$  complies with  $\mathcal{W}^3$  and is  
 179 loaded by  $\Theta_{,3}^2$ ,  $U_{3,33}^1$  and  $U_{\alpha,333}^0$ . The applied load is not globally self-equilibrating for each  
 180 individual loading. From the constitutive equation (30a) and the equilibrium equation (17a)  
 181 with  $p = 1$  it is deduced that :

$$U_{3,33}^1 = -\frac{p_3}{A_3} F. \quad (33)$$

182 Substituting this in  $\mathcal{W}^3$  ensures it is well-posed. Furthermore, it is also convenient to ensure  
 183 that the load is also self-equilibrating in bending. This is obtained, from the constitutive  
 184 equations (30b) and (30c) and the equilibrium equation (17b) for  $p = 1$ :

$$U_{1,333}^0 = \frac{V_1^2 - \mu_1 F}{D_1} \quad \text{and} \quad U_{2,333}^0 = \frac{V_2^2 - \mu_2 F}{D_2}. \quad (34)$$

Inserting these relations in problem  $\mathcal{W}^3$  leads to:

$$\mathcal{W}^3 : \begin{cases} \sigma_{3\alpha,\alpha}^2 + \tilde{\sigma}_{33}^{\chi_1} \frac{V_1^2}{D_1} + \tilde{\sigma}_{33}^{\chi_2} \frac{V_2^2}{D_2} + \left( \tilde{f}_3 - \frac{p_3}{A_3} \tilde{\sigma}_{33}^{e_3} - \frac{\mu_1}{D_1} \tilde{\sigma}_{33}^{\chi_1} - \frac{\mu_2}{D_2} \tilde{\sigma}_{33}^{\chi_2} \right) F = 0 & \text{on } \mathcal{S}^0, & (35a) \\ \sigma_{\alpha 3}^2 = C_{\alpha 3 \beta 3} 2\varepsilon_{\beta 3}^2 & \text{on } \mathcal{S}^0, & (35b) \\ 2\varepsilon_{\alpha 3}^2 = u_{3,\alpha}^3 + \tilde{u}_\alpha^{\chi_1} \frac{V_1^2}{D_1} + \tilde{u}_\alpha^{\chi_2} \frac{V_2^2}{D_2} - \left( \frac{p_3}{A_3} \tilde{u}_\alpha^{e_3} + \frac{\mu_1}{D_1} \tilde{u}_\alpha^{\chi_1} + \frac{\mu_2}{D_2} \tilde{u}_\alpha^{\chi_2} \right) F \\ \quad + y_\beta \varepsilon_{\beta \alpha} \Theta_{,3}^2 + U_{\alpha,3}^2 & \text{on } \mathcal{S}^0, & (35c) \\ \sigma_{\alpha 3}^2 n_\alpha = 0 & \text{on } \partial \mathcal{S}^0. & (35d) \end{cases}$$

185 The solution is parametrized by the shear forces  $V_\alpha^2$  the applied load  $F$  and higher-order  
 186 beam displacements. It writes as the linear superposition of each contributions:

$$u_3^3 = \tilde{u}_3^{V_\alpha} V_\alpha^2 + \tilde{u}_3^F F + \tilde{u}_3^{\chi_3} \Theta_{,3}^2 + y_\alpha U_{\alpha,3}^2 + U_3^3. \quad \text{with} \quad \langle \tilde{u}_3 \rangle = 0 \quad (36)$$

187 The longitudinal displacements  $\tilde{u}_3^{V_1}$  and  $\tilde{u}_3^{V_2}$  are warpings related to shear forces illustrated  
 188 in Figure (3b) and (3c). Indeed, considering the whole problem  $\mathcal{W}^3$  loaded exclusively with  
 189 shear forces, one can identify the corresponding Neumann problems in Saint Venant's beam  
 190 theory. Furthermore, the equilibrium equation (35a) considered with only the shear forces  
 191 loading and integrated on a partial section is actually Jouravskii's Formula [16] which gives  
 192 a fair estimate of shear stress in thin-walled beams. Finally,  $\tilde{u}_3^{V_1}$  and  $\tilde{u}_3^{V_2}$  are related to the  
 193 shear lag phenomenon in homogeneous thin-walled beams: when the beam is not enough  
 194 slender, the longitudinal stress  $\sigma_{33}$  is not exactly the linear distribution derived at leading  
 195 order (Equation (27c)).

<sup>3</sup> This simplification comes from the symmetry assumption (1) and the scaling chosen for  $f_\alpha$  such that bending deflection is of order 0.

*Macroscopic constitutive equations* From the solution of third order problems, the second-order stress may be written as:

$$\left\{ \begin{array}{l} \sigma_{\alpha\beta}^2 = \tilde{\sigma}_{\alpha\beta}^{\epsilon_3} U_{3,3}^2 + \tilde{\sigma}_{\alpha\beta}^{\chi_1} U_{1,33}^1 + \tilde{\sigma}_{\alpha\beta}^{\chi_2} U_{2,33}^1, \end{array} \right. \quad (37a)$$

$$\left\{ \begin{array}{l} \sigma_{\alpha 3}^2 = \tilde{\sigma}_{\alpha 3}^{V_\beta} V_\beta^2 + \tilde{\sigma}_{\alpha 3}^F F + \tilde{\sigma}_{\alpha 3}^{\chi_3} \Theta_{,3}^2, \end{array} \right. \quad (37b)$$

$$\left\{ \begin{array}{l} \sigma_{33}^2 = \tilde{\sigma}_{33}^{\epsilon_3} U_{3,3}^2 + \tilde{\sigma}_{33}^{\chi_1} U_{1,33}^1 + \tilde{\sigma}_{33}^{\chi_2} U_{2,33}^1 \end{array} \right. \quad (37c)$$

196 The traction and bending constitutive equations obtained from this stress distribution are  
197 identical to equations (30) incrementing the order. The second-order torsion is expressed as  
198 function of the macroscopic displacements and the applied load:

$$M_3^2 = D_3 \Theta_{,3}^2 + y_\alpha^S \epsilon_{\alpha\beta} V_\beta^2 + M_3^F F, \quad (38)$$

199 where the torsion induced by the non-uniform distribution of  $\tilde{f}_3$  in the section is  $M_3^F =$   
200  $\langle y_\gamma \epsilon_{\gamma\alpha} \tilde{\sigma}_{\alpha 3}^F \rangle$  and the shear center of the beam is defined as:

$$y_1^S = - \langle y_\alpha \epsilon_{\alpha\beta} \tilde{\sigma}_{\beta 3}^{V_2} \rangle \quad \text{and} \quad y_2^S = \langle y_\alpha \epsilon_{\alpha\beta} \tilde{\sigma}_{\beta 3}^{V_1} \rangle. \quad (39)$$

201 When the section presents two axes of symmetry, the shear center is in  $O$  but this is not  
202 always true.

### 203 2.1.5 Fourth-order and higher-order problems

*Transverse displacement* The transverse displacement  $u_\alpha^4$  is derived through  $\mathcal{T}^3$  and loaded  
by  $V_\alpha^2, F, F_{,3}, \Theta_{,33}^2, U_{3,3}^3$  and  $U_{\alpha,33}^2$ . Taking into account equilibrium equations (17c) and (17d)  
and constitutive equation (38), the problem may be recast only as function of  $F$  and  $F_{,3}, U_{3,3}^3$   
and  $U_{\alpha,33}^2$ . This substitution ensures also that the compatibility conditions (11) are satisfied.  
This leads to:

$$\mathcal{T}^4 : \left\{ \begin{array}{l} \sigma_{\alpha\beta,\beta}^3 + \left( \tilde{\sigma}_{\alpha 3}^F - \tilde{\sigma}_{\alpha 3}^{\chi_3} \frac{M_3^F}{D_3} \right) F_{,3} \\ \quad + \left( \tilde{f}_\alpha - \tilde{\sigma}_{\alpha 3}^{V_\beta} p_\beta - \frac{\tilde{\sigma}_{\alpha 3}^{\chi_3}}{D_3} \left( \mu_3 - y_\beta^S \epsilon_{\beta\gamma} p_\gamma \right) \right) F = 0 \quad \text{on } \mathcal{S}^0, \quad (40a) \\ \sigma_{\alpha\beta}^3 = C_{\alpha\beta\gamma\delta} \epsilon_{\delta\gamma}^3 + C_{\alpha\beta 33} \epsilon_{33}^3, \quad \sigma_{33}^3 = C_{33\alpha\beta} \epsilon_{\beta\alpha}^3 + C_{3333} \epsilon_{33}^3 \quad \text{on } \mathcal{S}^0, \quad (40b) \\ \epsilon_{\alpha\beta}^3 = u_{(\alpha,\beta)}^4 \quad \text{on } \mathcal{S}^0, \quad (40c) \\ \epsilon_{33}^3 = \left( \tilde{u}_3^F - \tilde{u}_3^{\chi_3} \frac{M_3^F}{D_3} \right) F_{,3} - \left( \tilde{u}_3^{V_\beta} p_\beta + \frac{\tilde{u}_3^{\chi_3}}{D_3} \left( \mu_3 - y_\beta^S \epsilon_{\beta\gamma} p_\gamma \right) \right) F \\ \quad + U_{3,3}^3 + y_\alpha U_{\alpha,33}^2 \quad \text{on } \mathcal{S}^0, \quad (40d) \\ \sigma_{\alpha\beta}^3 n_\beta = 0 \quad \text{on } \partial \mathcal{S}^0. \quad (40e) \end{array} \right.$$

204 The solution of this boundary value problem parametrized by the load  $F$ , its first gradient  
205  $F_{,3}$ , the elongation  $U_{3,3}^3$  and the curvatures  $U_{\alpha,33}^2$ . It writes as:

$$u_\alpha^4 = \tilde{u}_\alpha^F F + \tilde{u}_\alpha^{F\nabla} F_{,3} + \tilde{u}_\alpha^{\epsilon_3} U_{3,3}^3 + \tilde{u}_\alpha^{\chi_\beta} U_{\beta,33}^2 + U_\alpha^4 + y_\beta \epsilon_{\beta\alpha} \Theta^4, \quad (41)$$

206 The cross-section displacement  $\tilde{u}_\alpha^F$  is related to the non-uniform distribution in the section  
207 of the applied load  $\tilde{f}_\alpha$ . Similarly,  $\tilde{u}_\alpha^{F\nabla}$  is related to the variations of  $F$  and the non-uniform  
208 distribution of  $\tilde{f}_3$  in the section.

209 *Higher orders* The induction process may be pursued any higher order. This leads to the  
 210 derivation of new displacement localizations only related to higher derivatives of  $F$  relevant  
 211 for faster variations of  $F$ .

212 Note that, the use of the asymptotic expansion method is based on the scaling in Equat-  
 213 ion (3). Hence the rescaled coordinates  $y_i$  have been used in the expression of the auxiliary  
 214 problems  $\mathcal{T}^p$  and  $\mathcal{W}^p$ . However, the distinction between the two sets of coordinates is no  
 215 longer necessary in practice once the section modes are defined. The use of the coordinates  
 216  $y_i$  is therefore dropped in the following and replaced by the use of the coordinates  $x_i$ .

## 217 2.2 The higher-order beam model

218 *Families of kinematic enrichment* In the asymptotic expansion procedure, three families of  
 219 kinematic enrichment emerged. First, the rigid motion of the section was carried by the  
 220 six macroscopic variables  $U_i^p$ ,  $U_{\alpha,3}^p$  and  $\Theta_3^p$ . They are respectively related to the following  
 221 displacement modes:

$$\underline{\tilde{u}}^{U_1} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad \underline{\tilde{u}}^{U_2} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \quad \underline{\tilde{u}}^{U_3} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \quad \underline{\tilde{u}}^{\Theta_2} = \begin{pmatrix} 0 \\ 0 \\ -x_1 \end{pmatrix}, \quad \underline{\tilde{u}}^{\Theta_1} = \begin{pmatrix} 0 \\ 0 \\ x_2 \end{pmatrix}, \quad \underline{\tilde{u}}^{\Theta_3} = \begin{pmatrix} -x_2 \\ x_1 \\ 0 \end{pmatrix}. \quad (42)$$

222 Second, the six correctors related to the six beam resultants<sup>4</sup> were derived:  $\tilde{u}_\alpha^{e_3}$ ,  $\tilde{u}_\alpha^{\chi_1}$ ,  $\tilde{u}_\alpha^{\chi_2}$ ,  
 223  $\tilde{u}_3^{\chi_3}$ ,  $\tilde{u}_3^{V_1}$ ,  $\tilde{u}_3^{V_2}$ . They are also referred to as Saint Venant's modes [15, 12]. This collection of  
 224 12 modes (rigid and Saint-Venant) is denoted  $\mathbb{B}^{\text{SV}}$ . Third, a family of modes related to the  
 225 body force and its longitudinal variations was obtained:  $\tilde{\underline{u}}^F$ ,  $\tilde{\underline{u}}^{F\nabla}$ ,  $\tilde{\underline{u}}^{F\nabla^2}$  ..., which is denoted  
 226  $\mathbb{B}^f$ . This suggests gathering all these modes in the following kinematic approximation for  
 227 the 3D displacement:

$$\underline{u} = \sum_{k=1}^n \tilde{\underline{u}}^k(x_\alpha) X^k(x_3) \quad (43)$$

228 where  $n$  is the number of modes and  $X^k(x_3)$  are longitudinal unknown fields. It is demon-  
 229 strated in [19] that the modes generated for a single prescribed body load distribution  $f_i$  in  
 230 the cross-section is a Hilbert basis of the solution space for  $\underline{u}$ .

231 *Load superposition* With proper scaling, it is possible to consider other loadings in a separate  
 232 form between longitudinal coordinate and cross-section coordinates such as surface traction  
 233 on the lateral boundary of the cross-section as well as prescribed eigenstrains. Furthermore,  
 234 whereas most loadings in engineering practice comply with the separate form requested in  
 235 equation (6) the latter may be too constraining in some specific cases. The problem being  
 236 linear, it is possible to superpose loads. In that case, the collection of modes  $\tilde{\underline{u}}^i$  may become  
 237 linearly dependent and is orthogonalized.

238 In practice, it appears that decomposing a cross-section load distribution into several  
 239 distinct loadings improves the quality of the solution. For instance, in Equation (6), one may  
 240 modulate  $\tilde{f}_3(x_\eta)$  with  $F(x_3)$  separately from  $\tilde{f}_\alpha(x_\eta)$  with another function  $G(x_3)$ . However,  
 241 this doubles the number of kinematic degrees of freedom related to the applied load (third  
 242 family). The best trade off between the load decomposition and the accuracy of the solution  
 243 has not yet been explored in details.

<sup>4</sup> From the traction, bending and torsion constitutive equations (30) and (31),  $\tilde{u}_\alpha^{e_3}$ ,  $\tilde{u}_\alpha^{\chi_\beta}$  and  $\tilde{u}_3^{\chi_3}$  are directly related to  $N_3$ ,  $M_\beta$  and  $M_3$ .

244 *Minimum potential energy principle* The higher-order beam model is obtained, inserting  
 245 the approximated kinematics (43) in the minimum potential energy principle of the 3D  
 246 problem (2). Indeed, the variable separation between longitudinal and cross-section coordi-  
 247 nates allows the separation of the corresponding integrals. Since all cross-section modes are  
 248 known there remains only a boundary value problem related to the longitudinal coordinate.  
 249 The corresponding equilibrium equations write as:

$$\forall l, \quad X^k A_{kl} + X_{,3}^k (B_{kl} - B_{lk}) - X_{,33}^k C_{kl} - F_l = 0 \quad (44)$$

250 where:

$$\begin{aligned} A_{kl} &= \left\langle \tilde{u}_{i,\alpha}^k C_{i\alpha j\beta} \tilde{u}_{j,\beta}^l \right\rangle, & B_{kl} &= \left\langle \tilde{u}_i^k C_{i3j\beta} \tilde{u}_{j,\beta}^l \right\rangle, \\ C_{kl} &= \left\langle \tilde{u}_i^k C_{i3j3} \tilde{u}_j^l \right\rangle, & \text{and } F_k &= \left\langle \tilde{u}_i^k \tilde{f}_i \right\rangle. \end{aligned} \quad (45)$$

251 *Boundary conditions* In the 3D problem (2), the beam extremities were assumed fully  
 252 clamped. Considering the approximated kinematics (43), this is achieved enforcing  $X_i =$   
 253  $0$  at extremities. Other boundary conditions may be applied. Indeed, the first six modes  
 254 corresponds to the rigid motion of the section. Restraining only these degrees of freedom  
 255 is actually the boundary condition classically used in structural mechanics: warping and  
 256 transverse displacements are let free.

## 257 2.3 Applications

258 Two case study are briefly presented. The first case study illustrates the advantage of introduc-  
 259 ing displacement modes related to the distribution in the cross-section of the applied load. The  
 260 second case study was extended to eigenstrains and illustrates the possibility of describing  
 261 more accurately the effect of prestress in a beam. In both cases, the auxiliary problems (10)  
 262 and (13) generating the kinematic enrichment were solved with 2D quadratic Lagrange finite  
 263 elements. Two different strategies were used for the higher-order beam solution.

### 264 2.3.1 Cantilever box girder beam under a concentrated load

265 A cantilever beam of span 10 m with a box section 3 m wide is investigated (Figure 4). The  
 266 width and the height of the box are 1 m. The thickness of the walls is 5 cm. The beam is fully  
 267 clamped at its first extremity and loaded by a concentrated force in the middle of the section  
 268 at the other extremity (Figure 4).

269 In addition to the six rigid modes (42) and the six Saint Venant modes ( $\mathbb{B}^{SV}$ ), 3 warping  
 270 and 3 transverse displacement modes (Figure 5) are included in the kinematics ( $\mathbb{B}^f$ ). These  
 271 modes clearly illustrate the local influence of the distribution in the section of the concentrated  
 272 load.

273 Because they lead to ordinary differential equations, beam models are suited for closed-  
 274 form solutions. The homogeneous part of equations (44) have solutions of the form  $e^{kx_3}$   
 275 which may be found explicitly solving a quadratic eigenvalue problem [28]. This technique  
 276 was used in [13] in order to find the solution of the beam loaded at its extremity. It presents  
 277 the advantage to yield a solution extremely rapidly. However, because it may include sharp  
 278 decaying exponential functions, its implementation requires specific treatment. Furthermore,  
 279 it is restricted to linear problems with specific longitudinal distribution of the applied load.  
 280 Figure 4 shows the reconstructed beam solution. The local settlement related to the application  
 281 of the concentrated force is very well captured.

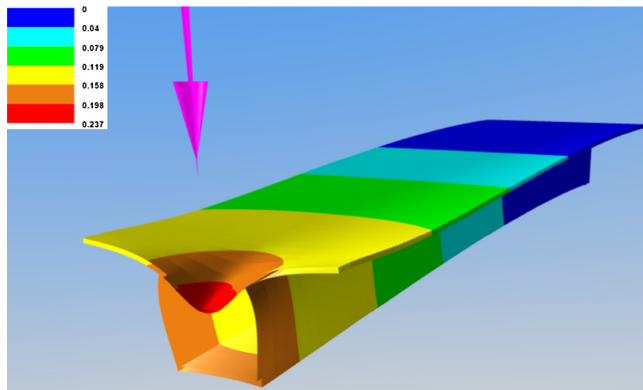


Fig. 4: Cantilever box girder beam under applied load [13]

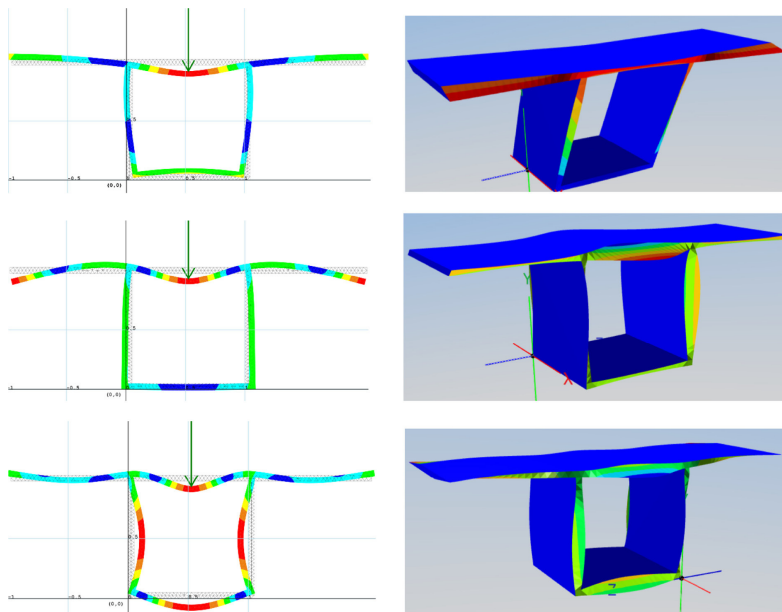


Fig. 5: Six displacement modes related to the applied load. Transverse modes (left) and warping modes (right). [13]

### 282 2.3.2 Prestressed cable in a cantilever beam

283 The higher-order beam model is further illustrated with a cantilever concrete beam prestressed  
 284 with a steel cable. The section of the beam is represented in Figure 6. The beam is 20 m long.  
 285 The concrete domain is denoted by  $\Omega_c$  and the steel domain by  $\Omega_s$ . A constant eigenstrain  
 286  $\boldsymbol{\varepsilon}^* = \varepsilon_{33}^* \boldsymbol{e}_3 \otimes \boldsymbol{e}_3$  is applied in  $\Omega_s$ , with  $\varepsilon_{33}^* = 7 \cdot 10^{-3}$ , corresponding to 23 MN pretension in  
 287 the cable. Both materials are homogeneous and isotropic with:  $(E, \nu)_{\text{concrete}} = (35 \text{ GPa}, 0.2)$   
 288 and  $(E, \nu)_{\text{steel}} = (200 \text{ GPa}, 0.3)$ . Note that, a real concrete beam would require additional  
 289 reinforcement bars as well as a non-linear constitutive behavior. This simplified example is

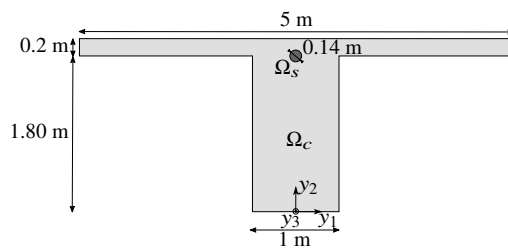


Fig. 6: Section of the prestressed beam

290 chosen here to illustrate the ability of eigenstrain modes to capture rather fast variations of  
 291 the strain in the section.

292 The sectional modes are computed up to the fourth gradient of the eigenstrain. The 5  
 293 first orthonormalized modes associated to the eigenstrain  $\underline{\underline{u}}^T$ ,  $\underline{\underline{u}}^{\nabla T}$ ,  $\underline{\underline{u}}^{\nabla T^2}$ ,  $\underline{\underline{u}}^{\nabla T^3}$  and  $\underline{\underline{u}}^{\nabla T^4}$ ,  
 294 denoted  $\mathbb{B}^e$ , are represented in Figure 7. These three transverse modes and two warping  
 modes clearly illustrate the action of the cable in the concrete beam.

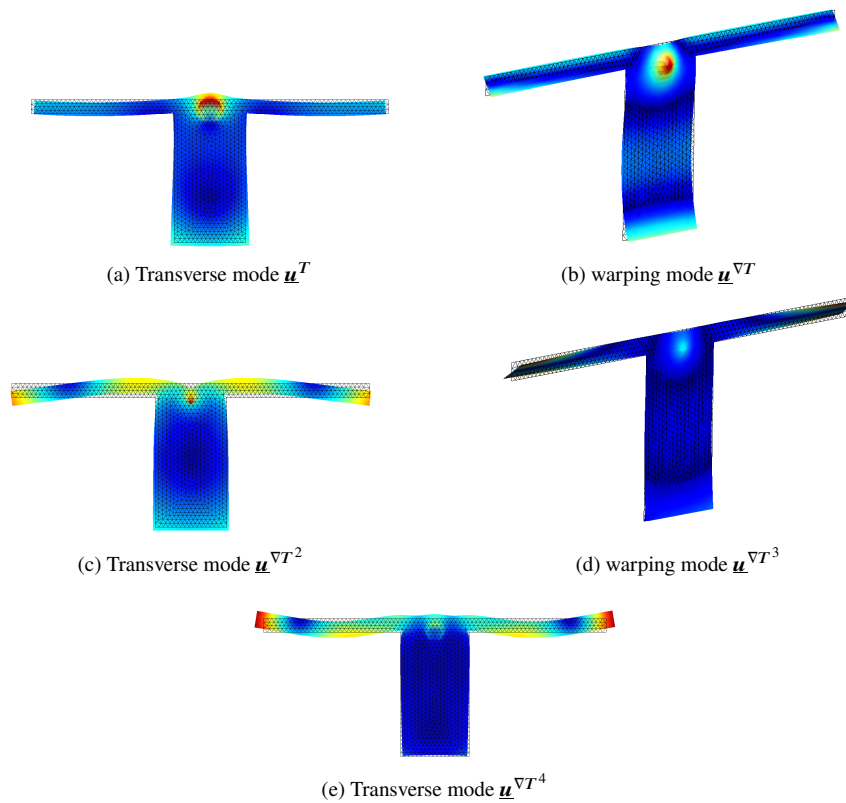


Fig. 7: The 5 eigenstrain modes related to the prestress in the steel cable used in case study 2.

	reference model	higher-order beam model
type of elements	15-nodes pentahedron	6-nodes triangle + 41 longitudinal knots
number of elements	99680	1788 + 1
CPU computation time	1805 s	24 s

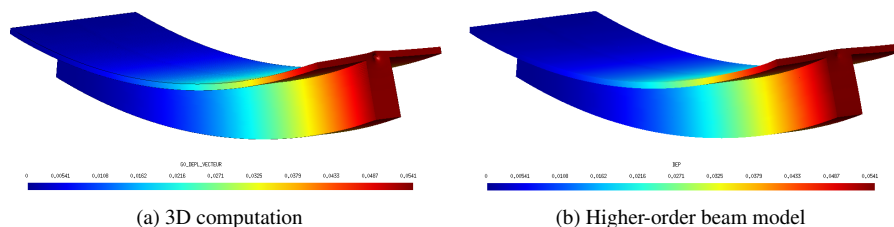
Table 1: Main features of the 3D solution and solution  $S$ 

Fig. 8: Deformed structure under pre-tensioned steel cable (amplification factor = 100), [9]

295 The higher-order beam model was discretized with NURBS shape functions. Contrary to  
 296 the closed-form solution previously mentioned, this allows to apply various load distributions.  
 297 Additionally, NURBS shape functions are known to mitigate locking phenomena. This was  
 298 confirmed in a detailed study of the present implementation in [9].

299 The reconstructed solution is presented in Figure 8. As expected, the prestressed cable  
 300 compresses and raises the beam. The higher-order beam model captures transverse dis-  
 301 placements illustrated by the lowering of the edges of the table. It also captures warping  
 302 displacements illustrated by the punching effect of the cable which can be observed at the  
 303 end of the beam. A 3D reference solution was also computed by means of *Code\_Aster* on a  
 304 very similar mesh. The deformed beam is also presented in Figure 8 and the computation data  
 305 is summarized in Table 1. It appears that, the model presented here shows very satisfying  
 306 results with a significantly reduced computational cost. Indeed, only very few additional  
 307 modes (3 to 5) and their corresponding beam DOF were required for capturing fairly well the  
 308 applied eigenstrain. These time performances can still largely be improved by more advanced  
 309 implementations and numerical techniques.

310 However, detailed analysis shows that in the vicinity of the boundaries, the quality of  
 311 the solution is not as satisfying as in the bulk of the beam (see details in [9]). This is not  
 312 surprising since higher-order convergence results has only been obtained in configurations  
 313 where boundary layers related to the beam extremities are not present. In order to better  
 314 describe the mechanical behavior close to boundary conditions, the approach developed  
 315 independently by *Strains Engineering* consists in the introduction of new modes specific to  
 316 these boundary conditions in the reduced basis.

### 317 3 The Asymptotic Expansion Load Decomposition elasto-plastic beam model

318 Introducing elasto-plastic behavior is more challenging. The inherent non-linearity of plas-  
 319 ticity and the incremental nature of plastic analysis makes the definition of a relevant kine-  
 320 matics more difficult. Two main approaches are followed when solving an elasto-plastic



321 beam problem: 1D elasto-plastic beam model based on a priori cross-section analysis or 3D  
322 elasto-plastic beam models based on a 3D beam kinematics.

323 The first natural approach is to express the plastic flow in terms of generalized beam  
324 variables and to solve an elasto-plastic 1D problem. This requires the elasto-plastic analysis  
325 of the cross-section for pure or combined generalized stresses and the derivation of the  
326 corresponding yield surface. The cross-section analysis may be incremental or based on  
327 limit analysis but assumes a uniform distribution of generalized stresses in the longitudinal  
328 direction: normal force, shear forces, bending moments and torque. A key difficulty is  
329 the derivation of a yield surface directly function of the beam generalized stress taking  
330 into account correctly their possible interactions as well as hardening. There were recent  
331 improvements in this direction, approximating the yield surface with facets or ellipsoids [5].  
332 Once the yield surface is defined, there remains to compute the elasto-plastic response of the  
333 beam, either with closed form solutions [25], limit analysis [22] or by means of finite element  
334 approximations [3, 23]. This approach has the advantage to present fast computation time,  
335 since only a 1D elasto-plastic problem needs to be solved. However, its accuracy remains  
336 limited by the beam theory assumptions. First, it cannot handle local phenomena related to  
337 the distribution of the applied load as well as to the boundary conditions. Second, it provides  
338 only an averaged description of the actual stress in the beam.

339 In order to improve the accuracy of the beam model, the second classical approach  
340 consists in setting a beam kinematics expressing the 3D displacement field in a separate form  
341 between the transverse coordinates and the longitudinal coordinate. This kinematics may be  
342 defined a priori or may evolve during the incremental procedure. For a fixed increment of the  
343 generalized displacements, the corresponding 3D stress is computed and the yield criterion  
344 is expressed locally. A local algorithm such as the radial return is processed on the whole  
345 body to compute the local plastic state of the beam. This locally admissible stress state is  
346 integrated on each cross-section yielding the corresponding longitudinal distribution of the  
347 beam generalized stresses. Finally, the beam global equilibrium is ensured with a standard  
348 Newton-Raphson procedure. The main difficulty lies again in the definition of a relevant  
349 kinematics able to describe the displacement related to plastic flow.

350 Most approaches where the kinematics is fixed a priori rely on the ones already discussed  
351 in linear elasticity such as Euler-Bernoulli, Timoshenko kinematics or even Saint-Venant  
352 solution, eventually with non-linear geometric corrections. Once the kinematics is defined,  
353 there remains to choose the number of integration points in the cross-section in order to  
354 compute precisely the local plastic flow. Multiplying integration points improves the accuracy  
355 of the results at the price of a higher computation time of the cross-sections integrals. This  
356 is the spirit of multi-fiber beam models (see for instance [18]). Another direction is to enrich  
357 arbitrarily the section kinematics with degrees of freedom not necessarily related to classical  
358 cross-section displacements. This concept was formalized extensively by Carrera et al [7]  
359 and co-workers.

360 Because plastic flow may not be easily known *a priori* a natural improvement of the  
361 preceding methods is to update the beam kinematics during the load increments. This is the  
362 direction followed here using the asymptotic expansion.

### 363 3.1 Adaptation of the higher-order beam model to the elasto-plastic behavior

364 The linear higher-order beam model presented in the previous section is extended to elasto-  
365 plasticity in the small strains framework. Hence, the boundary value problem expressed in

Equation (2) is now considered with a  $J_2$  elasto-plastic constitutive law and will be solved classically following a Newton-Raphson incremental scheme.

As for linear elasticity, a 3D approximated kinematics is formulated in a separated form in order to perform the dimension reduction. The first collection of modes to take into account is the basis of Saint Venant modes  $\mathbb{B}^{SV}$  as well as the basis of force modes  $\mathbb{B}^f$  related to the applied load described previously. Nevertheless, this kinematics is not sufficient for describing accurately the possibly discontinuous plastic flow which may occur in the cross section. Therefore, the plastic strain computed at a given iteration of the Newton-Raphson procedure is taken into account for enriching the kinematics of the following iteration. This is possible using the procedure described in the previous section for a fixed plastic strain  $\boldsymbol{\varepsilon}^p$  distribution in the cross-section. Considering now the whole beam,  $\boldsymbol{\varepsilon}^p$  is not longitudinally uniform. Hence, several chosen cross-sections may be used for taking snapshots of the plastic strain in order to sufficiently enrich the kinematics of the model. These new *plastic modes* are computed and added to the kinematics on the fly. The basis of modes specific to a cross-section plastic strain distribution is denoted by  $\mathbb{B}^\varepsilon$ . Finally, the kinematics of the model is evolving during the Newton-Raphson procedure and is the union of the basis  $\mathbb{B}^{SV}$ ,  $\mathbb{B}^f$  and  $\mathbb{B}^\varepsilon$ . This union of basis is orthonormalized to form the total basis  $\mathbb{B}$  with a total number of modes  $n_{\text{mod}}$ .

This approach presents two major advantages. First, it does not require additional elasto-plastic computations in the cross-section. Second, the number of beam degrees of freedom remains very limited (about 20) thanks to the sparsity of the kinematics. From the optimality result proved in [19], this approach is expected to be more efficient than arbitrary kinematic refinements.

Note that, contrary to Nonuniform Transformation Field Analysis [20, 21, 14] where a basis of plastic strains is introduced with the corresponding plastic multipliers, in the present approach, *displacement* plastic modes are added to the *total* 3D displacement approximation and plasticity is processed at each integration point of the 3D body.

### 3.2 The elasto-plastic algorithm

The implementation of the general framework introduced in the previous section is now detailed. This requires first the definition of the numerical approximation of the 3D body. Then, the incremental resolution of the elasto-plastic problem is adapted so that processing the local constitutive equations remains standard whereas the global equilibrium iterations are performed with the reduced basis.

#### 3.2.1 Numerical approximation of the higher-order beam model

The approach suggested in the previous section requires the definition of a 3D mesh of the beam composed of cross-sections meshes positioned along the longitudinal direction (Figure 9). Indeed, these cross-sections will be the domain of integration of the constitutive law.

*Longitudinal discretization* A longitudinal discretization of the beam is defined for the generalized displacements  $X^m(x_3)$  introduced in Equation (43). The same collection of NURBS basis functions for each  $X^m(x_3)$  is chosen:

$$X^m(x_3) = \sum_{i=1}^{n_{\text{NURBS}}} N^i(x_3) X^{m,i} \quad (46)$$

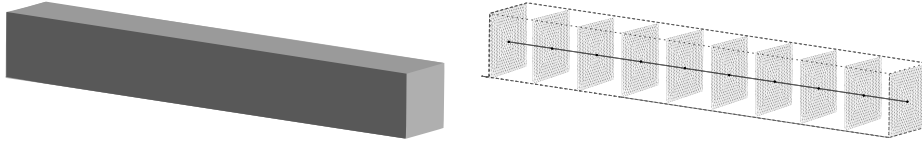


Fig. 9: Discretization of a square beam

407 where  $N^i(x_3)$  are the NURBS interpolation function and  $X^{m,i}$  are the corresponding degrees  
 408 of freedom. A set of  $N_s > n_{\text{NURBS}}$  longitudinal integration points is also defined for the  
 409 integration of the interpolation functions. It is natural to place the cross-section meshes at  
 410 the positions of these longitudinal integration points.

411 *Cross-section discretization* The cross-section mesh used for the computation of the modes  
 412 is the same as the one used in Section 2.3.2: the modes are computed by means of quadratic  
 413 Lagrange triangle elements:

$$\tilde{\mathbf{u}}^m(x_\alpha) = \sum_{j=1}^{n_{\text{sec}}} \mathbf{L}^j(x_\alpha) \tilde{u}^{m,j} \quad (47)$$

414 where  $n_{\text{sec}}$  is the number of nodes in the section,  $\mathbf{L}^j(x_\alpha)$  are Lagrange interpolation functions  
 415 and  $\tilde{u}^{m,j}$  are the nodal values of the displacement.

416 The local state variables,  $\Delta \boldsymbol{\varepsilon}$ ,  $\Delta \boldsymbol{\varepsilon}^p$  and  $\Delta \boldsymbol{\sigma}$  are computed in the  $N_s$  cross-sections meshes  
 417 at the Gauss points of the quadratic triangle elements.

418 *Plastic-mode cross-section* During the computation, sections where a plastic strain is not  
 419 zero are collected. All cross-sections where plasticity occurs could be used for the compu-  
 420 tation of the plastic modes: for each plastic strain distribution in each cross section, one or  
 421 several modes could be computed. However, it would excessively increase the number of  
 422 generalized displacement degrees of freedom  $n_{\text{dof}}$  and also increase the computation time  
 423 dedicated to the corresponding modes. In order to limit the number of plastic modes to a few,  
 424 only one cross-section called *plastic-mode cross-section* is chosen for taking snapshots of  
 425 the plastic strain distribution. As a first approach, this choice is based on an educated guess.

### 426 3.2.2 Adaptation of the Newton-Raphson procedure

427 *Formulation of the tangent stiffness of the beam model* For a given basis of  $n_{\text{mod}}$  displacement  
 428 modes, the numerical approximation of the total displacement may be written as follows:

$$\mathbf{u}(\mathbf{x}) = \sum_{m=1}^{n_{\text{mod}}} \sum_{i=1}^{n_{\text{NURBS}}} \sum_{j=1}^{n_{\text{sec}}} \mathbf{L}^j(x_\alpha) N^i(x_3) \tilde{u}^{m,j} X^{m,i} = \sum_{i=1}^{n_{\text{NURBS}}} \sum_{j=1}^{n_{\text{sec}}} \mathbf{L}^j(x_\alpha) N^i(x_3) u^{i,j} \quad (48)$$

429 where the  $n_{3\text{D}} = n_{\text{NURBS}} \times n_{\text{sec}}$  local displacement degrees of freedom are:

$$u^{i,j} = \sum_{m=1}^{n_{\text{mod}}} \tilde{u}^{m,j} X^{m,i}. \quad (49)$$

430 Considering the second form of (48), it appears that the 3D strain  $\boldsymbol{\varepsilon}(\mathbf{u})$  and consequently the  
 431 local constitutive equation may be directly computed from  $u^{i,j}$  without the need to specify

the basis  $\mathbb{B}$ . Hence, provided the finite element solution is stored as the collection of the  $u^{i,j}$ , the local integration of the constitutive equations as well as the computation of the local elasto-plastic tangent stiffness remain unchanged compared to a 3D formulation.

For a fixed basis  $\mathbb{B}$ , injecting the numerical approximation of the kinematics (48) into the principle of virtual work corresponding the elasto-plastic 3D problem (2) leads to the expression of the residual expressed in terms of the increment of the  $n_{\text{dof}} = n_{\text{mod}} \times n_{\text{NURBS}}$  generalized displacement degrees of freedom  $\Delta X^{m,i}$  and the corresponding test degrees of freedom. The standard Newton-Raphson procedure is used in order to cancel this residual which leads to the following formal reduced equilibrium equation:

$$[\mathbf{K}^{\text{ep}}]_{\mathbb{B}} \{\delta \mathbf{X}\}_{\mathbb{B}} = \{\mathbf{R}\}_{\mathbb{B}}, \quad (50)$$

where  $[\mathbf{K}^{\text{ep}}]_{\mathbb{B}} \in (\mathbb{R}^{n_{\text{dof}}})^2$  is the global tangent stiffness matrix of the beam model expressed in basis  $\mathbb{B}$ , computed with the local elasto-plastic tangent stiffness,  $\{\delta \mathbf{X}\}_{\mathbb{B}}$  is the finite element vector of the generalized degrees of freedom  $\delta X^{m,i}$  and  $\{\mathbf{R}\}_{\mathbb{B}} \in \mathbb{R}^{n_{\text{dof}}}$  is the residual vector. Because, the tangent stiffness as well as the residual both depend on the choice of the basis  $\mathbb{B}$ , they need to be updated each time the basis is changed.

Significant computational time is gained because  $n_{\text{dof}}$  which sets the size of the tangent stiffness is much smaller than the rather large  $n_{3\text{D}}$  which is required for a sufficiently detailed description of the fields in the cross-section.

*Description of the numerical procedure* The basis of modes  $\mathbb{B}$  is first initialized and is composed  $\mathbb{B}^{\text{SV}}$  and  $n_{\text{fAE}}$  modes associated to the applied load  $\mathbb{B}^f$ . While increments do not generate plastic flow, the basis  $\mathbb{B}$  remains unchanged. The global tangent stiffness corresponds to the elastic one and each increment is solved in one iteration.

Let assume that increment  $n$  generates a non-vanishing plastic strain  $\Delta \boldsymbol{\varepsilon}_n^{\text{p}}$  at the first iteration  $k = 1$ . In this case, before starting the second iteration, the basis of modes is enriched and orthonormalized with  $n_{\text{pAE}}$  modes computed from the plastic strain distribution  $\Delta \boldsymbol{\varepsilon}_n^{\text{p}}$  observed in the plastic-mode cross-section, following [9]. This also requires the update of the residual.

It has been noticed from experience that plastic modes computed at subsequent iterations of the increment were very similar. Therefore the basis  $\mathbb{B}$  used at iteration  $k = 2$  is kept until the convergence of the increment is reached. However, the converged plastic strain of the increment  $\Delta \boldsymbol{\varepsilon}_n^{\text{p}}$  may have changed. Hence, at the first iteration  $k = 1$  of the following increment  $n + 1$ , the basis  $\mathbb{B}$  is updated, replacing only plastic modes with new ones. Again, at the second iteration  $k = 2$  the basis is updated and then remains fixed until the convergence of the increment. This choice of updating the plastic modes only at the first two iterations of the increment remains valid as long as the load increments are not too important.

### 3.3 Application to a cantilever beam

To illustrate the efficiency of the model presented, a steel beam clamped at one end and loaded on its free end is investigated. The beam is a wide flange beam HE600M. This cross-section is class 1 in Eurocode 3, meaning that the beam reaches its limit of elasticity with no risk of local buckling. The geometry of the 6 m long beam is detailed in Figure 10. A load is applied with eccentricity at the top edge of the free end of the beam, as represented in Figures 10 and 11. The force  $F$  is applied on the length  $l = 230$  mm. The study is decomposed into 10 time steps, and the load is incrementally increased of 0.25 MN at each step until it reaches

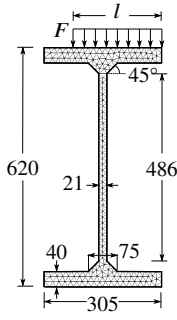


Fig. 10: Dimensions (mm) of the HE600M section, mesh and applied load

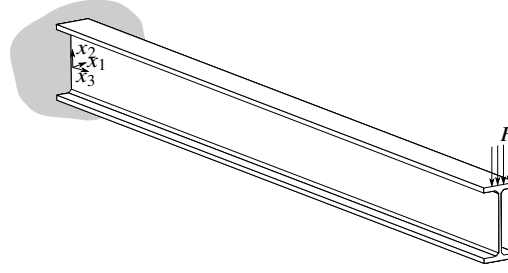


Fig. 11: 3D representation of the HE600M cantilever beam loaded at its end

474 2.5 MN and then it is released following the reversed path. The following values are chosen  
 475 for the Young's modulus the Poisson's ratio, the strain hardening modulus and the yield  
 476 modulus:

$$E = 210 \text{ GPa}, \quad \nu = 0.3, \quad H = 0.02E, \quad \sigma_0 = 235 \text{ MPa} \quad (51)$$

477 *Higher-order beam solution  $S_{1D}$*  The section of the solution  $S_{1D}$  is meshed with 399  
 478 quadratic triangle Lagrange elements, as shown in Figure 10. The NURBS interpolation  
 479 functions are represented in Figure 12. The corresponding integration sections are repre-  
 480 sented in Figure 13. The mesh is refined close to the clamped extremity since plasticity is  
 expected to occur mainly at this location.

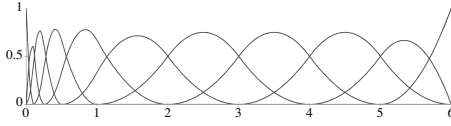


Fig. 12: Second-order NURBS basis functions used for the longitudinal interpolation of the element

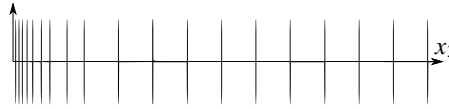


Fig. 13: Longitudinal mesh composed of 19 integration sections

481 The plastic-strain cross-section is placed at  $x_3 = 0.25$  m at the 5<sup>th</sup> integration point. The  
 482 number of force modes is  $n_{fAE} = 4$ , and of plastic modes is  $n_{pAE} = 9$ . During the computation,  
 483 the maximum number of modes in the basis is 22. Indeed, in the orthormalization procedure,  
 484 redundant modes are discarded. The number of interpolation shape functions being 11, the  
 485 maximum number of degrees of freedom during the computation is therefore  $n_{dof} = 242$ .  
 486

487 *3D Reference solution* A 3D reference solution is computed with the finite element software  
 488 *Code\_Aster*. The beam is meshed by extruding a cross-section with 430 triangles along  
 489 the longitudinal axis. The longitudinal discretization is the same as for the beam model  
 490 and forms 7740 prismatic elements in total. The prismatic elements are interpolated with  
 491 quadratic functions.

492 *Comparison with the 3D reference solution* The beam solution is 80 times faster to compute.  
 493 The corresponding deformed structure is presented in Figure 14. The torque due to the  
 494 eccentricity of the load induces a longitudinal rotation of the cross-section, and the transverse  
 part of the load induces a bending of the beam.

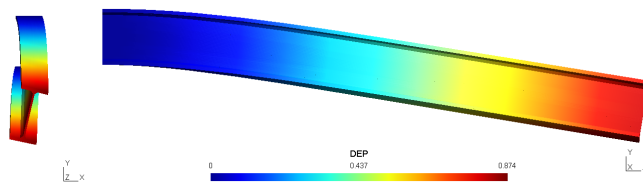


Fig. 14: Deformed shape of the beam after the 10 load increments (solution  $S_{1D}$ )

495 In order to compare both solutions, the deflection at point A placed on the free extremity  
 496 of the beam ( $x_3 = 6$  m) is represented in Figure 15 during the 20 time steps of the study. The

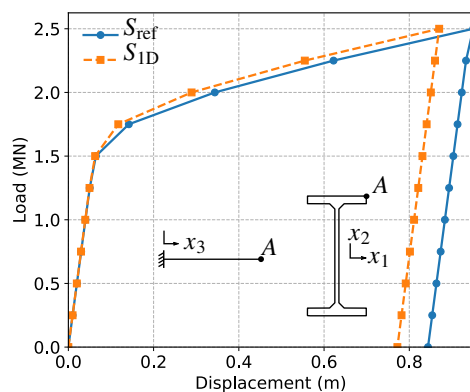


Fig. 15: Deflection at point A for loading and unloading

497 results obtained with the beam solution  $S_{1D}$  are consistent with the reference solution. The  
 498 beam solution satisfactorily captures the plastic branch despite a low kinematic hardening  
 499 ( $H = 0.02E$ ). The curve of  $S_{1D}$  is slightly above the curve of  $S_{ref}$ : for  $u_A = 0.8$  m, solution  $S_{1D}$   
 500 associates a force 2, 42% higher than the force obtained by  $S_{ref}$ . As expected, the unloading  
 501 occurring between time steps  $t_{11}$  and  $t_{20}$  is elastic. The gap between the beam solution and  
 502 the 3D solution induces a difference between the two residual displacements observed at  
 503  $t_{20}$ . For the solution  $S_{1D}$  considered here, the relative distance between the two solutions  
 504 at  $t_{20}$  is of 8.51%. This relative distance originates from the gap observed at  $t_{10}$  which  
 505 is maintained between  $t_{11}$  and  $t_{20}$  since the unloading is elastic. A residual displacement  
 506 closer to the 3D reference could be obtained with more refined longitudinal meshes and  
 507 with higher interpolation order for the interpolation functions. But in regards with the very  
 508 low computational time offered by the beam solution, the results obtained can be considered  
 509 satisfying for engineering applications.  
 510

511 In order to assess the accuracy of the beam solution when compared to the reference  
 512 solution the six components of the plastic strain computed by the solution  $S_{1D}$  and by the  
 513 reference solution at  $x_3 = 0,5$  m for the given displacement  $u_A = 0.8$  m of point A, are  
 514 presented in Figure 16. All the variables presented for a fixed displacement of point A are  
 515 obtained by linear interpolations between the increments defined in Section 3.3 and figured  
 by markers in Figure 15.

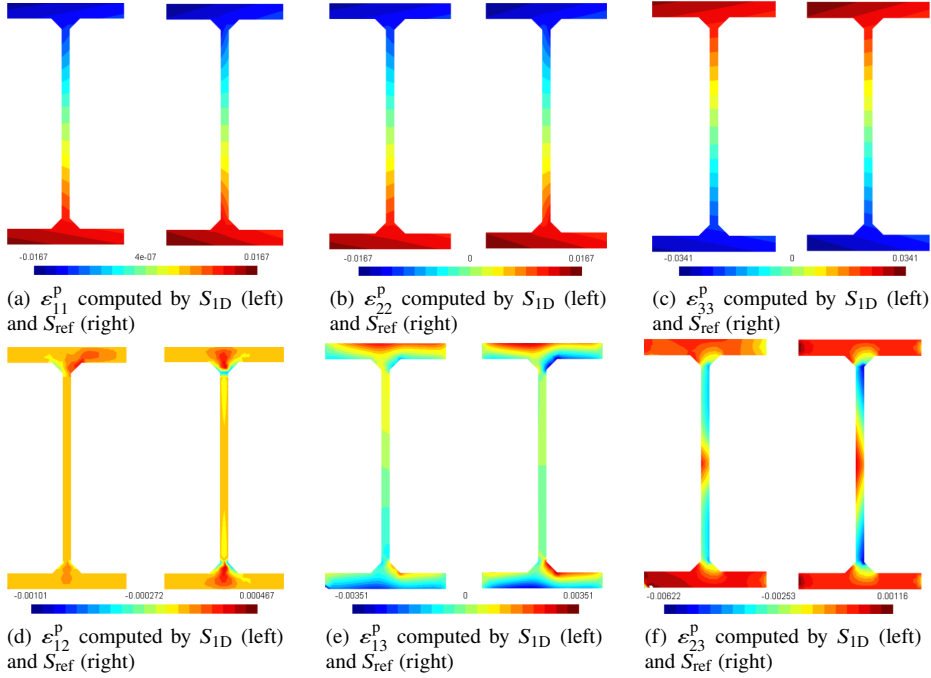


Fig. 16: Plastic strain in solutions  $S_{1D}$  and  $S_{ref}$  close to the clamped extremity at  $x_3 = 0.5$  m for  $u_A = 0.8$  m

516

517 The axial plastic strain presented in Figures 16a to 16c shows that nearly all parts of  
 518 the section have reached the elastic limit. As expected, the eccentricity of the load on the  
 519 free extremity of the beam creates a slightly uneven progression of plasticity in the section.  
 520 Therefore the highest values of the plastic strain components are observed at the top left and  
 521 the bottom left of the section where the absolute values of the stresses are largest. The plastic  
 522 strain computed by  $S_{1D}$  is slightly lower than the plastic strain computed by  $S_{ref}$  for each  
 523 component. A late detection of plasticity due to the longitudinal refinement is suspected to  
 524 originate this phenomenon.

525 The non-axial components presented in Figures 16d to 16f seem less satisfying but  
 526 their amplitude is about 10 times lower than the axial components. Thus, the beam solution  
 527 presented here shows satisfying results with a good comparison with the 3D solution.

## 528 4 Discussion and outlooks

529 Several applications of the AELD higher-order elasto-plastic beam model were presented.  
530 The model is based on an enrichment of the reduced kinematics updated on the fly and does  
531 not need any *a priori* knowledge on the solution of the problem.

532 Both in linear elasticity framework and in  $J_2$  elastoplasticity, the beam model required  
533 a computation about 80 times shorter than for the reference 3D solution computed on  
534 *Code\_Aster* with comparable meshes. These gains in computation time are already very  
535 interesting and could be even larger by means of parallelization, in particular for the compu-  
536 tation of the tangent stiffness matrix.

537 The numerical differences between the beam solution and the reference solution for  
538 the examples presented are low, and could still be lowered. Indeed, the computation of the  
539 displacement modes is optimal only far from boundary conditions. At the clamped extremity  
540 the local stress varies rapidly. The model could therefore be improved if displacement modes  
541 specific to the boundary conditions were computed and added to the kinematics of the  
542 model. Furthermore, the choice of the plastic-mode cross-section was arbitrary and could be  
543 automated based for instance on the location of the first occurrence of plasticity in the beam.

544 We conclude that the present beam model offers already interesting perspectives for  
545 engineering applications on the cloud. Nevertheless, it is meant to be validated on more  
546 complex case-studies.

547 Several extensions of the linear elastic AELD model are straightforward. The low and  
548 medium frequency dynamic behavior is easy to derive including inertia contributions from  
549 the assumed kinematics [26]. Buckling analysis may also be adapted [27], as the eigenstrains  
550 enrichment is a suitable basis for representing the pre-stress in the beam and deriving the  
551 geometric stiffness operator. Similarly, other weak couplings (thermal, humidity, creep etc.)  
552 or non standard physics [17] may be incorporated in the model. . Furthermore, the elasto-  
553 plastic beam model has been presented here with an isotropic material and a  $J_2$  yield criterion.  
554 Its adaption to different yield criteria is easy and the extension to more complex materials  
555 like reinforced concrete was achieved with a Rankine yield criterion in [11].

556 Finally, as long as strains remains small, the kinematic enrichment provided by the  
557 asymptotic expansion remains relevant. Hence, the authors are considering a co-rotational  
558 formulation of the AELD beam model in order to introduce geometric non-linearities related  
559 to large displacements and rotations.

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