

Modeling of bending-torsion couplings in active-bending structures. Application to the design of elastic gridshell.



École des Ponts
ParisTech

Thèse n. xxxxx
présenté le 01 décembre 2017
à l'Ecole des Ponts ParisTech
laboratoire Navier
Université Paris-Est

pour l'obtention du grade de Docteur ès Sciences
par

Lionel du Peloux

acceptée sur proposition du jury:

Prof Name Surname, président du jury
Prof Name Surname, directeur de thèse
Prof Name Surname, rapporteur
Prof Name Surname, rapporteur
Prof Name Surname, rapporteur

Paris, Ecole des Ponts ParisTech, 2016

Contents

5	Elastic rod : equilibrium approach	1
5.1	Introduction	1
5.1.1	Goals and contribution	1
5.1.2	Related work	1
5.1.3	Overview	2
5.2	Dynamical equations for Kirchhoff rods	2
5.2.1	Assumptions	2
5.2.2	Balance of linear momentum	3
5.2.3	Balance of angular momentum	4
5.3	Equations of motion	5
5.3.1	Constitutive equations	5
5.3.2	Internal forces and moments	6
5.3.3	Rod dynamic	6
5.4	Geometric interpretation	7
5.5	Numerical resolution	14
5.5.1	Main hypothesis	14
5.5.2	Discret beam model	14
5.5.3	Discret bending moments and curvatures	14
5.5.4	Discret twisting moment	16
5.5.5	Discret axial force	16
5.5.6	Discret shear force	16
5.5.7	Interpolation	17
5.6	Conclusion	17

5 Elastic rod : equilibrium approach

5.1 Introduction

Ici on explique que l'approche par les équations d'équilibre est beaucoup plus directe que l'approche énergétique.

5.1.1 Goals and contribution

Dans ce chapitre, après un bref rappel sur le cadre mathématique d'étude des courbes paramétrique de l'espace, on présente les notions de courbures et de torsion géométrique associées au repère de fraient. On montre ensuite le cas plus général d'un repère mobile quelconque attaché à une courbe gamma. On définit enfin la particularité d'un repère mobile adapté à un courbe, et on présente, en sus du repère de Frenet, une approche différente pour accrocher des repères le long d'une courbe (Bishop / RMF / Zéro-twisting frame)

Ici il faudrait préciser la terminologie des auteurs / équations / hypothèses : Euler-Bernoulli, Navier-Bernoulli, Kirchhoff, Love, Clebesh, Cosserat, Vlassov

5.1.2 Related work

On peu s'instruire dans la publi de Dill [Dil92]. Regarder en particulier le premier chapitre de l'HDR de Neukirch [Neu09]. Regarder également la chronologie des modèles proposée dans la thèse de Theetten [The07]. Pourquoi pas proposer une frise chronologique + un tableau de synthèse des hyptohèses.

[Dil92] (author?) [Neu09] [ABW99] [Hoo06] [LL09] [Spi08] [Ant05]

[Neu09] : p69 - [Dil92] : p16

Dans les tentatives dans notre domaine, citer :

Départ : [Day65] : already includes a rotational DOF !! [Wak80] [Bar99] : revue intéressante de la DR.

3 pts classique : [ABW99] [DBC06]

2 x 3pts : [BAK13]

6 Dofs : [DKZ14]

4Dofs : [dPTL⁺15] [DZK16]

Dans le champ de l'animation avec élément finis [DLP13] [MPW14]

5.1.3 Overview

Résumé du chapitre

5.2 Dynamical equations for Kirchhoff rods

A thorough order-of-magnitude analysis is exposed in [Dil92, BEL⁺93]

A larger scope full development is given in [Ant05]

5.2.1 Assumptions

- axial extension is small
- sections remain planar in the deformed configuration
- sections remain perpendicular to the centerline in the deformed configuration

ces équations sont valables à l'ordre 2 en α où :

$$\alpha = \max_{s \in [0, L]} \{ |\kappa(s)|h, |\bar{\kappa}(s)|h, h/L \} \quad (5.1)$$

On fait par ailleurs l'hypothèse inextensible pour la dérivation du repère matériel.

dynamical equations

Writing the balance of linear and angular momentum of a beam slice of infinitesimal yields to the dynamic Kirchhoff equations for a slender beam. An extensive proof of this development is available in [Dil92].

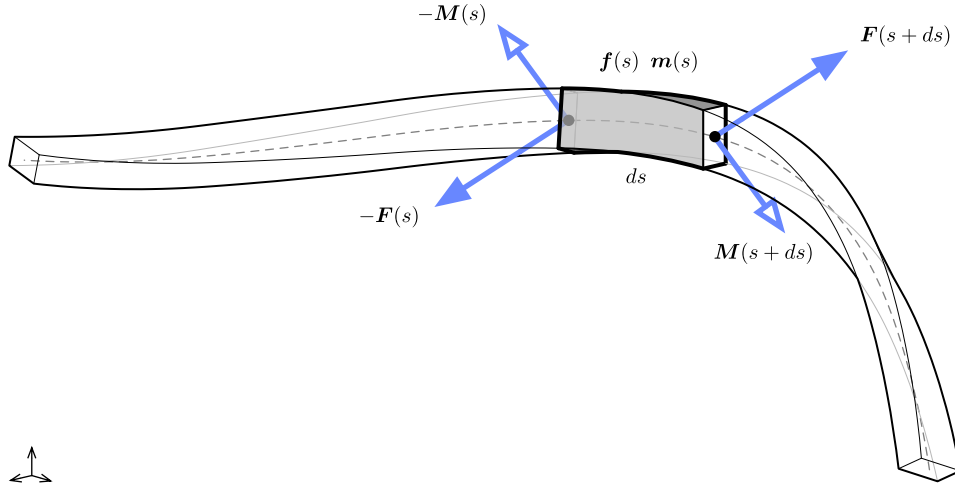


Figure 5.1 – Internal forces (\mathbf{F}) and moments (\mathbf{M}) acting on an infinitesimal beam slice of length ds . The beam is also subject to distributed external forces (\mathbf{f}) and moments (\mathbf{m}). By convention, internal forces and moments are forces and moments applied by the right part to the left part of the beam.

1 2 3

5.2.2 Balance of linear momentum

On fait un bilan sur une tranche d'épaisseur ds , de centre de gravité G positionné en \mathbf{x}_G :

$$\mathbf{F}(s+ds) - \mathbf{F}(s) + \mathbf{f}(s)ds = \left(\frac{\partial \mathbf{F}}{\partial s}(s) + \mathbf{f}(s) \right) ds = (\rho S ds) \ddot{\mathbf{x}}_G \quad (5.2)$$

Which leads to the first equation of Kirchhoff law :

$$\frac{\partial \mathbf{F}}{\partial s} + \mathbf{f} = \rho S \ddot{\mathbf{x}}_G \quad (5.3)$$

¹“The principal normal, binormal, and torsion of the axis, viewed as an element of a space curve, have no special significance in the theory of rods. Use of those special directions as base vectors does not simplify the theory and can mislead the reader into attributing significance to them when none exists. In particular, the curvature of the rod should not be confused with the curvature of the space curve which the axis forms.” [Dil92, p.5]

²“Kirchhoff’s theory can only apply to that class of problems for three dimensional bodies such that the loads on the sides are relatively small and slowly varying. The dominate mode of deformation must be a global bending and twisting with small axial extension. If there are substantial local variations in curvatures or substantial transverse shears, his theory of bending of rods will not provide a satisfactory first approximation.” [Dil92, p.18]

³“There are no constitutive relations for F_1 or F_2 . They are determined by the balance of momentum as in the elementary linear theory of bending of rods.” [Dil92, p.15]

5.2.3 Balance of angular momentum

On fait un bilan sur une tranche d'épaisseur ds , de centre de gravité G positionné en \mathbf{x}_G . On applique le théorème du moment cinétique dans un référentiel inertiel :

$$\begin{aligned} \frac{d}{dt}(dI_G) &= \mathbf{M}(s+ds) - \mathbf{M}(s) + \mathbf{m}(s)ds + \left(\frac{1}{2}ds\mathbf{x}'\right) \times \mathbf{F}(s+ds) + \left(-\frac{1}{2}ds\mathbf{x}'\right) \times -\mathbf{F}(s) \\ &= \left(\frac{\partial \mathbf{M}}{\partial s}(s) + \mathbf{m}(s) + \mathbf{x}' \times \mathbf{F}(s)\right) ds \end{aligned} \quad (5.4)$$

L'évolution temporelle des vecteurs matériels est cette fois décrite par un vecteur de Darboux temporel (spin vector in [BEL⁺93] noté $\mathbf{\Lambda}$ tel que : Compatibility equation between the curvature vector and the spin vector ($\kappa\dot{\mathbf{b}} - \mathbf{\Lambda}' = \mathbf{\Lambda} \times \kappa\mathbf{b}$).

$$\dot{\mathbf{d}}_i(s) = \mathbf{\Lambda}(t) \times \mathbf{d}_i(s) \quad , \quad \mathbf{\Lambda}(t) = \begin{bmatrix} \Lambda_3(t) \\ \Lambda_1(t) \\ \Lambda_2(t) \end{bmatrix} \quad (5.5)$$

Les lois de composition / dérivation de la mécanique nous permettent décrire :

$$\frac{d}{dt}(dI_G) = dI_G \dot{\mathbf{\Lambda}} + \mathbf{\Lambda} \times dI_G \quad (5.6)$$

Qu'est ce qu'on met dans dI_G ? Et bien tout simplement l'opérateur d'inertie de la section, qui s'exprime à l'aide des moments quadratiques des directions principales de la façon suivante, dans la base des directions principales d'inertie au premier ordre en ds :

$$dI_G = \begin{bmatrix} dI_{G3} & 0 & 0 \\ 0 & dI_{G1} & 0 \\ 0 & 0 & dI_{G2} \end{bmatrix} \simeq \rho ds \begin{bmatrix} I_1 + I_2 & 0 & 0 \\ 0 & I_1 & 0 \\ 0 & 0 & I_2 \end{bmatrix} \quad (5.7)$$

Where :

$$dI_{G3} = \int_V \rho(x_1^2 + x_2^2) dV \simeq \rho ds \int_V (x_1^2 + x_2^2) dx_1 dx_2 \simeq \rho ds(I_1 + I_2) \quad (5.8a)$$

$$dI_{G1} = \int_V \rho(x_2^2 + x_3^2) dV \simeq \rho ds \int_V x_2^2 dx_1 dx_2 \simeq \rho ds I_1 \quad (5.8b)$$

$$dI_{G2} = \int_V \rho(x_1^2 + x_3^2) dV \simeq \rho ds \int_V x_1^2 dx_1 dx_2 \simeq \rho ds I_2 \quad (5.8c)$$

Et l'on peut alors écrire la seconde loi de Kirchhoff sous la forme suivante :

$$\frac{\partial \mathbf{M}}{\partial s}(s) + \mathbf{m}(s) + \mathbf{x}' \times \mathbf{F}(s) = \rho \begin{bmatrix} (I_1 + I_2)\dot{\Lambda}_3 + (I_2 - I_1)\Lambda_1\Lambda_2 \\ I_1(\dot{\Lambda}_1 + \Lambda_2\Lambda_3) \\ I_2(\dot{\Lambda}_2 - \Lambda_3\Lambda_1) \end{bmatrix} \quad (5.9)$$

On peut alors conclure sur l'expression de l'équation de kirchoff ^{4 5} :

$$\frac{\partial \mathbf{M}}{\partial s}(s) + \mathbf{m}(s) + \mathbf{d}_3 \times \mathbf{F}(s) = I_1 \mathbf{d}_1 \times \ddot{\mathbf{d}}_1 + I_2 \mathbf{d}_2 \times \ddot{\mathbf{d}}_2 \quad (5.10)$$

⁴Recall that : $\ddot{\mathbf{d}}_i = \mathbf{\Lambda} \times \mathbf{d}_i$

⁵Remark that : $(\mathbf{\Lambda} \times \dot{\mathbf{d}}_i) \times \mathbf{d}_i = \Lambda_i(\mathbf{\Lambda} \times \dot{\mathbf{d}}_i)$

5.3 Equations of motion

5.3.1 Constitutive equations

"An order-of-magnitude analysis leading ..."

Attention, pas d'effort normal par loi constitutive en principe car on est dans un modèle inextensible. L'effort normal est calculé par la loi d'équilibre avec les moments et/ou efforts tranchants. Ici, on postulera tout de même une telle loi constitutive pour la résolution numérique. Ce qui nous amène à considérer une tige quasiment inextensible.

point à creuser. en gros je suis entrain de dire que dans le modèle classique à 3DOF type Douthe ou Barnes, il n'est pas nécessaire d'introduire la raideur axiale (mais alors où intervient la section ?). L'effort normal est déduit des équations d'équilibre.

En fait cela ne semble pas possible. Il faut alors revenir à l'équation constitutive qui donne l'effort normal, mais alors quid de l'hypothèse quasistatique ?

Dans le fond, l'hypothèse d'inextensibilité c'est dire que les déformations axiales sont négligeable devant les autres modes de déformation (flexion et/ou torsion). Mais pour caractériser l'effort normal lui même, il faut bien considérer une elongation.

Ou alors, peut-être qu'il faut comprendre que l'effort normal est déduit uniquement des conditions aux limites et/ou éventuellement des efforts extérieurs appliqués à la centerline.

Pour comprendre le traitement de l'inextensibilité, regarder [Ant05] p50. Qu'apporte l'hypothèse d'inextensibilité. Est-elle raisonnable. Tps de calcul par rapport au cas extensible.

$$\mathbf{N} = ES(\|\mathbf{d}'_3\| - \|\bar{\mathbf{d}}'_3\|)\mathbf{d}_3 \quad (5.11a)$$

$$\mathbf{M}_1 = EI_1(\kappa_1 - \bar{\kappa}_1)\mathbf{d}_1 \quad (5.11b)$$

$$\mathbf{M}_2 = EI_2(\kappa_2 - \bar{\kappa}_2)\mathbf{d}_2 \quad (5.11c)$$

$$\mathbf{Q} = [GJ(\theta' - \bar{\theta}') - EC_w(\theta''' - \bar{\theta}''')]\mathbf{d}_3 \quad (5.11d)$$

where :

$$I_1 = \int_S x_2^2 dx_1 dx_2 \quad (5.12)$$

$$I_2 = \int_S x_1^2 dx_1 dx_2 \quad (5.13)$$

$$J = \int_S (x_1^2 + x_2^2 + x_1 \frac{\partial \phi}{\partial x_2} - x_2 \frac{\partial \phi}{\partial x_1}) dx_1 dx_2 \quad (5.14)$$

with $\phi(x_1, x_2)$ is the warping function of the cross section.

5.3.2 Internal forces and moments

Efforts internes de coupure :

$$\mathbf{F}_{int} = N\mathbf{d}_3 + F_1\mathbf{d}_1 + F_2\mathbf{d}_2 \quad (5.15a)$$

$$\mathbf{M}_{int} = Q\mathbf{d}_3 + M_1\mathbf{d}_1 + M_2\mathbf{d}_2 \quad (5.15b)$$

Efforts externes appliqués linéiques :

$$\mathbf{f}_{ext} = f_3\mathbf{d}_3 + f_1\mathbf{d}_1 + f_2\mathbf{d}_2 \quad (5.16a)$$

$$\mathbf{m}_{ext} = m_3\mathbf{d}_3 + m_1\mathbf{d}_1 + m_2\mathbf{d}_2 \quad (5.16b)$$

5.3.3 Rod dynamic

First Kirchhoff law projecting on the material frame basis :

$$N' + \kappa_1 F_2 - \kappa_2 F_1 + f_3 = \rho S \ddot{x}_3 \quad (5.17a)$$

$$F_1' + \kappa_2 N - \tau F_2 + f_1 = \rho S \ddot{x}_1 \quad (5.17b)$$

$$F_2' - \kappa_1 N + \tau F_1 + f_2 = \rho S \ddot{x}_2 \quad (5.17c)$$

Qu'on écrit vectoriellement :

$$\mathbf{F}' + \boldsymbol{\Omega} \times \mathbf{F} + \mathbf{f}_{ext} = \rho S \ddot{\mathbf{x}} \quad \text{with} \quad \mathbf{F}' = [F_1' \quad F_2' \quad N']^T \quad (5.18)$$

This is nothing but the application of the transport theorem when differentiating a vector expressed in the material frame :

$$\left. \frac{\partial \mathbf{F}}{\partial s} \right|_{global} = \left. \frac{\partial \mathbf{F}}{\partial s} \right|_{local} + \boldsymbol{\Omega}(s) \times \mathbf{F} \quad (5.19)$$

Second Kirchhoff law projecting on the material frame basis :

$$Q' + \kappa_1 M_2 - \kappa_2 M_1 + m_3 = (I_1 + I_2) \dot{\Lambda}_3 + (I_2 - I_1) \Lambda_1 \Lambda_2 \quad (5.20a)$$

$$M_1' + \kappa_2 Q - \tau M_2 - F_2 + m_1 = I_1 (\dot{\Lambda}_1 + \Lambda_2 \Lambda_3) \quad (5.20b)$$

$$M_2' - \kappa_1 Q + \tau M_1 + F_1 + m_2 = I_2 (\dot{\Lambda}_2 - \Lambda_3 \Lambda_1) \quad (5.20c)$$

Qu'on écrit vectoriellement :

$$\mathbf{M}' + \boldsymbol{\Omega} \times \mathbf{M} + \mathbf{m}_{ext} + \mathbf{d}_3 \times \mathbf{F} = I_1 \mathbf{d}_1 \times \ddot{\mathbf{d}}_1 + I_2 \mathbf{d}_2 \times \ddot{\mathbf{d}}_2 \quad (5.21)$$

$$\text{with} \quad \mathbf{M}' = [M_1' \quad M_2' \quad Q']^T \quad (5.22)$$

This is nothing but the application of the transport theorem when differentiating a vector

expressed in the material frame :

$$\left. \frac{\partial \mathbf{M}}{\partial s} \right|_{global} = \left. \frac{\partial \mathbf{M}}{\partial s} \right|_{local} + \boldsymbol{\Omega}(s) \times \mathbf{M} \quad (5.23)$$

5.4 Geometric interpretation

Ici, on peut mettre l'interprétation géométrique (cf pdf LDP notes). Cela consiste essentiellement à 2/3 schémas bien pensés à produire + à écrire les projections au 1er ordre.

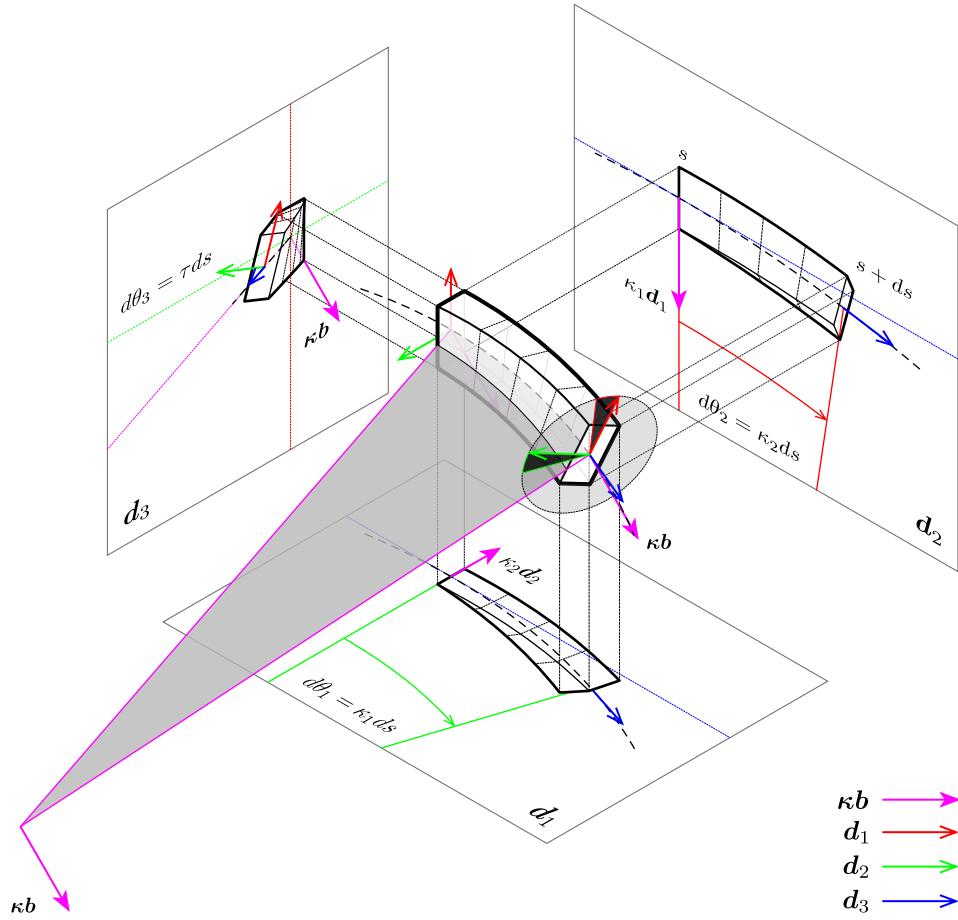
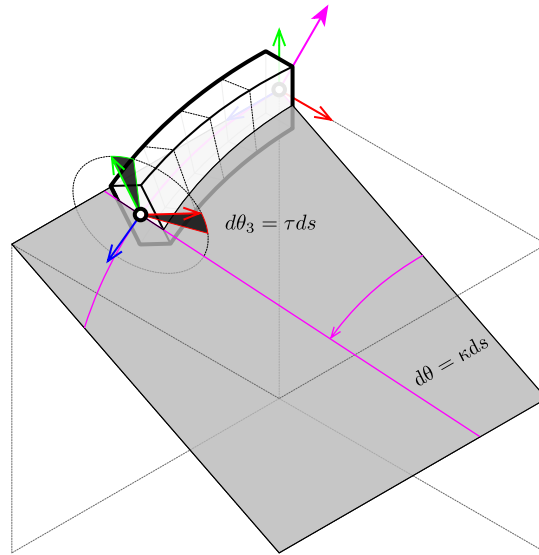
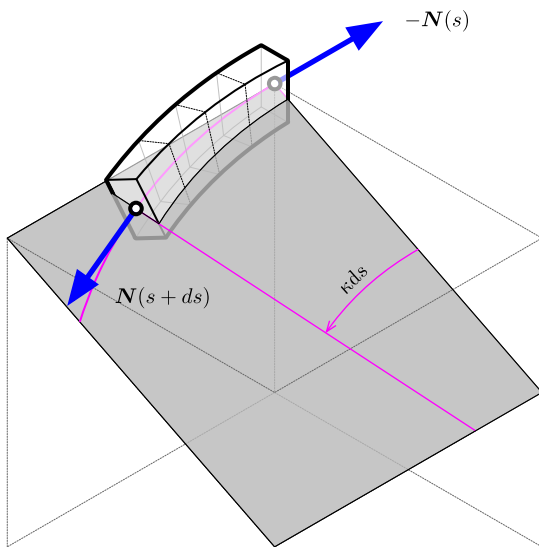


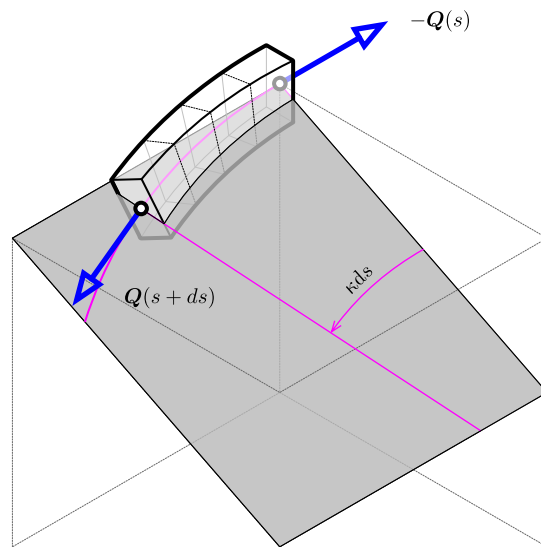
Figure 5.2 – Osculating circles for a spiral curve at different parameters.



(a) Infinitesimal deformation.



(b) Contributions of the internal forces.



(c) Contributions of the internal moments.

Figure 5.3 – Influence of the centerline curvature (κ) in the deviation of internal forces and moments along the centerline.

Contributions to the balance of forces

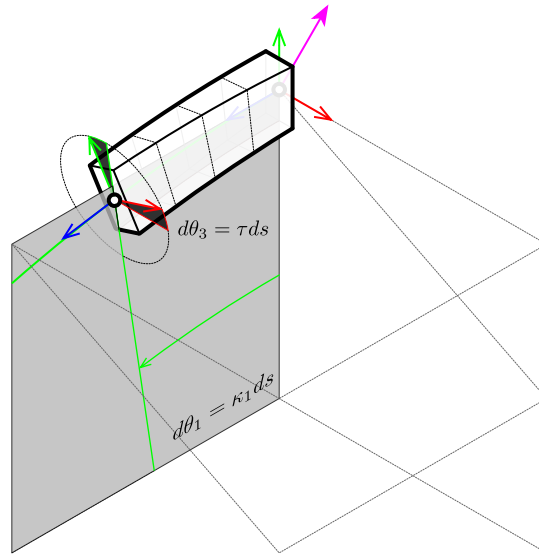
$N(s+ds)$ is deviated from $\mathbf{d}_3(s)$ by an angle $d\theta = \kappa ds$ along ds (fig. 5.3b). Thus, its overall contribution to the balance of forces over $\mathbf{d}_3(s)$ is :

$$N(s+ds) \cos(\kappa ds) - N(s) = N'(s)ds + o(ds)$$

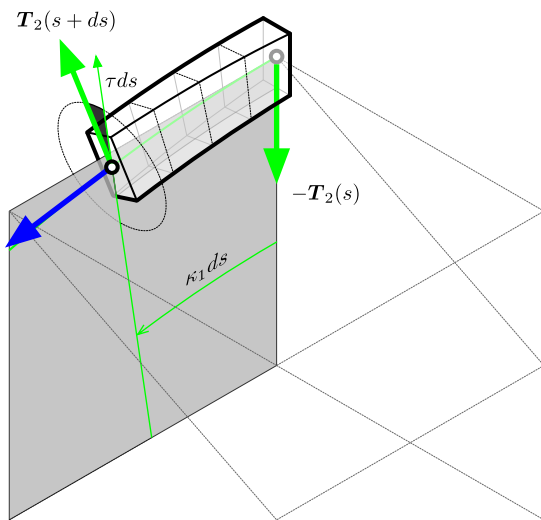
Contributions to the balance of moments

$Q(s+ds)$ is deviated from $\mathbf{d}_3(s)$ by an angle $d\theta = \kappa ds$ along ds (fig. 5.3c). Thus, its overall contribution to the balance of moments over $\mathbf{d}_3(s)$ is :

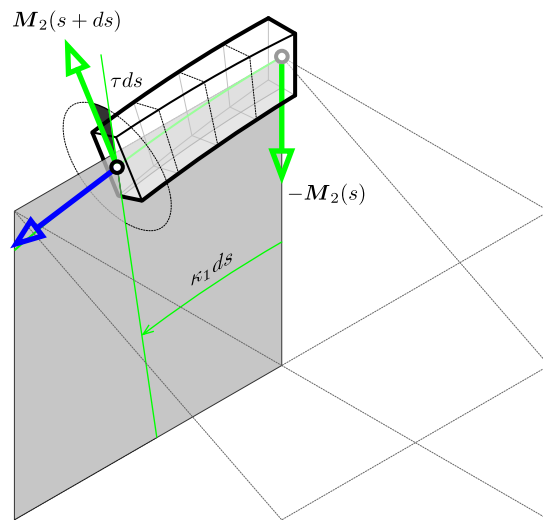
$$Q(s+ds) \cos(\kappa ds) - Q(s) = Q'(s)ds + o(ds)$$



(a) Infinitesimal deformation.



(b) Contributions of the internal forces.



(c) Contributions of the internal moments.

Figure 5.4 – Influence of the first material curvature (κ_1) in the deviation of internal forces and moments along the centerline.

Contributions to the balance of forces

$T_2(s + ds)$ is deviated from $\mathbf{d}_2(s)$ by the combined angles $d\theta_3 = \tau ds$ and $d\theta_2 = \kappa_2 ds$ along ds (fig. 5.4b). Thus, its overall contribution to the balance of forces over $\mathbf{d}_1(s)$ is :

$$-T_2(s + ds) \sin(\tau ds) \cos(\kappa_2 ds) = -\tau T_2(s) ds + o(ds)$$

$T_2(s + ds)$ is deviated from $\mathbf{d}_2(s)$ by the combined angles $d\theta_3 = \tau ds$ and $d\theta_1 = \kappa_1 ds$ along ds (fig. 5.4b). Thus, its overall contribution to the balance of forces over $\mathbf{d}_2(s)$ is :

$$-T_2(s) + T_2(s + ds) \cos(\tau ds) \cos(\kappa_1 ds) = T_2'(s) ds + o(ds)$$

$T_2(s + ds)$ is deviated from $\mathbf{d}_2(s)$ by the combined angles $d\theta_3 = \tau ds$ and $d\theta_1 = \kappa_1 ds$ along ds (fig. 5.4b). Thus, its overall contribution to the balance of forces over $\mathbf{d}_3(s)$ is :

$$T_2(s + ds) \cos(\tau ds) \sin(\kappa_1 ds) = \kappa_1 T_2(s) ds + o(ds)$$

$N(s + ds)$ is deviated from $\mathbf{d}_3(s)$ by the combined angles $d\theta_2 = \kappa_2 ds$ and $d\theta_1 = \kappa_1 ds$ along ds (fig. 5.4b). Thus, its overall contribution to the balance of forces over $\mathbf{d}_2(s)$ is :

$$-N(s + ds) \cos(\kappa_2 ds) \sin(\kappa_1 ds) = -\kappa_1 N(s) ds + o(ds)$$

Contributions to the balance of moments

$T_2(s + ds)$ is deviated from the plane normal to $\mathbf{d}_1(s)$ by the angle $d\theta_3 = \tau ds$ along ds (fig. 5.4b). It produces a moment around \mathbf{d}_1 with the lever arm $b = \cos(\kappa_2 ds) ds$. Thus, its overall contribution to the balance of moments over $\mathbf{d}_1(s)$ is :

$$-T_2(s + ds) \cos(\tau ds) (\cos(\kappa_2 ds) ds) = -T_2(s) ds + o(ds)$$

$M_2(s + ds)$ is deviated from $\mathbf{d}_2(s)$ by the combined angles $d\theta_3 = \tau ds$ and $d\theta_2 = \kappa_2 ds$ along ds (fig. 5.4c). Thus, its overall contribution to the balance of moments over $\mathbf{d}_1(s)$ is :

$$-M_2(s + ds) \sin(\tau ds) \cos(\kappa_2 ds) = -\tau M_2(s) ds + o(ds)$$

$M_2(s + ds)$ is deviated from $\mathbf{d}_2(s)$ by the combined angles $d\theta_3 = \tau ds$ and $d\theta_1 = \kappa_1 ds$ along ds (fig. 5.4c). Thus, its overall contribution to the balance of moments over $\mathbf{d}_2(s)$ is :

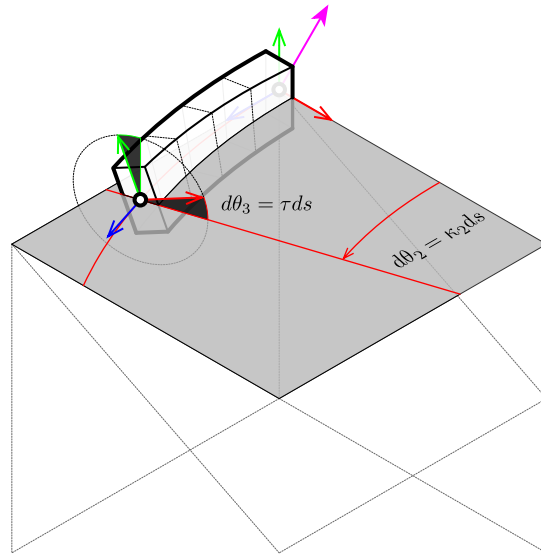
$$-M_2(s) + M_2(s + ds) \cos(\tau ds) \cos(\kappa_1 ds) = M_2'(s) ds + o(ds)$$

$M_2(s + ds)$ is deviated from $\mathbf{d}_2(s)$ by the combined angles $d\theta_3 = \tau ds$ and $d\theta_1 = \kappa_1 ds$ along ds (fig. 5.4c). Thus, its overall contribution to the balance of moments over $\mathbf{d}_3(s)$ is :

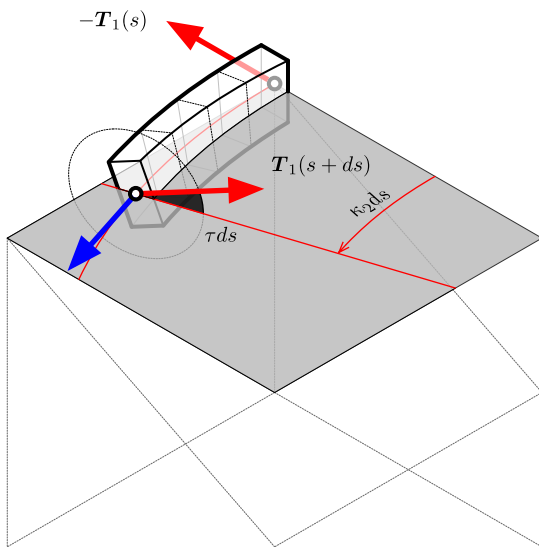
$$M_2(s + ds) \cos(\tau ds) \sin(\kappa_1 ds) = \kappa_1 M_2(s) ds + o(ds)$$

$Q(s + ds)$ is deviated from $\mathbf{d}_3(s)$ by the combined angles $d\theta_2 = \kappa_2 ds$ and $d\theta_1 = \kappa_1 ds$ along ds (fig. 5.4c). Thus, its overall contribution to the balance of moments over $\mathbf{d}_2(s)$ is :

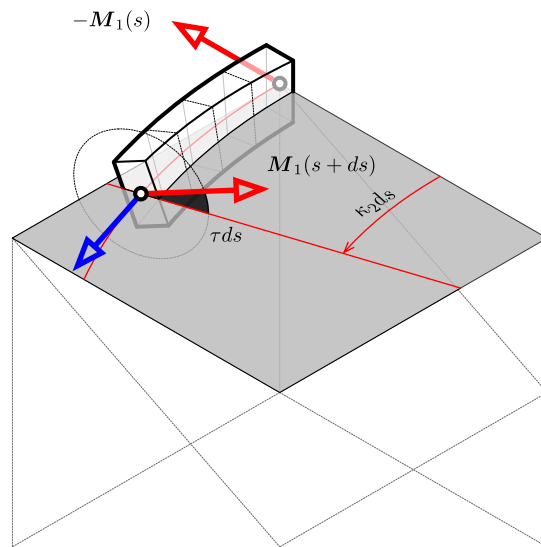
$$-Q(s + ds) \cos(\kappa_2 ds) \sin(\kappa_1 ds) = -\kappa_1 Q(s) ds + o(ds)$$



(a) Infinitesimal deformation.



(b) Contributions of the internal forces.



(c) Contributions of the internal moments.

Figure 5.5 – Influence of the second material curvature (κ_2) in the deviation of internal forces and moments along the centerline.

Contributions to the balance of forces

$T_1(s + ds)$ is deviated from $\mathbf{d}_1(s)$ by the combined angles $d\theta_3 = \tau ds$ and $d\theta_2 = \kappa_2 ds$ along ds (fig. 5.5b). Thus, its overall contribution to the balance of forces over $\mathbf{d}_1(s)$ is :

$$-T_1(s) + T_1(s + ds) \cos(\tau ds) \cos(\kappa_2 ds) = T_1'(s) ds + o(ds)$$

$T_1(s + ds)$ is deviated from $\mathbf{d}_1(s)$ by the combined angles $d\theta_3 = \tau ds$ and $d\theta_1 = \kappa_1 ds$ along ds (fig. 5.5b). Thus, its overall contribution to the balance of forces over $\mathbf{d}_2(s)$ is :

$$T_1(s + ds) \sin(\tau ds) \cos(\kappa_1 ds) = \tau T_1(s) ds + o(ds)$$

$T_1(s + ds)$ is deviated from $\mathbf{d}_1(s)$ by the combined angles $d\theta_3 = \tau ds$ and $d\theta_2 = \kappa_2 ds$ along ds (fig. 5.5b). Thus, its overall contribution to the balance of forces over $\mathbf{d}_3(s)$ is :

$$-T_1(s + ds) \cos(\tau ds) \sin(\kappa_2 ds) = -\kappa_2 T_1(s) ds + o(ds)$$

$N(s + ds)$ is deviated from $\mathbf{d}_3(s)$ by the combined angles $d\theta_1 = \kappa_1 ds$ and $d\theta_2 = \kappa_2 ds$ along ds (fig. 5.5b). Thus, its overall contribution to the balance of forces over $\mathbf{d}_1(s)$ is :

$$N(s + ds) \cos(\kappa_1 ds) \sin(\kappa_2 ds) = \kappa_2 N(s) ds + o(ds)$$

Contributions to the balance of moments

$T_1(s + ds)$ is deviated from the plane normal to $\mathbf{d}_2(s)$ by the angle $d\theta_3 = \tau ds$ along ds (fig. 5.5b). It produces a moment around \mathbf{d}_2 with the lever arm $b = \cos(\kappa_1 ds) ds$. Thus, its overall contribution to the balance of moments over $\mathbf{d}_2(s)$ is :

$$T_1(s + ds) \cos(\tau ds) (\cos(\kappa_1 ds) ds) = T_1(s) ds + o(ds)$$

$M_1(s + ds)$ is deviated from $\mathbf{d}_1(s)$ by the combined angles $d\theta_3 = \tau ds$ and $d\theta_2 = \kappa_2 ds$ along ds (fig. 5.5c). Thus, its overall contribution to the balance of moments over $\mathbf{d}_1(s)$ is :

$$-M_1(s) + M_1(s + ds) \cos(\tau ds) \cos(\kappa_2 ds) = M_1'(s) ds + o(ds)$$

$M_1(s + ds)$ is deviated from $\mathbf{d}_1(s)$ by the combined angles $d\theta_3 = \tau ds$ and $d\theta_2 = \kappa_2 ds$ along ds (fig. 5.5c). Thus, its overall contribution to the balance of moments over $\mathbf{d}_2(s)$ is :

$$M_1(s + ds) \sin(\tau ds) \cos(\kappa_2 ds) = \tau M_1(s) ds + o(ds)$$

$M_1(s + ds)$ is deviated from $\mathbf{d}_1(s)$ by the combined angles $d\theta_3 = \tau ds$ and $d\theta_2 = \kappa_2 ds$ along ds (fig. 5.5c). Thus, its overall contribution to the balance of moments over $\mathbf{d}_3(s)$ is :

$$-M_1(s + ds) \cos(\tau ds) \sin(\kappa_2 ds) = -\kappa_2 M_1(s) ds + o(ds)$$

$Q(s + ds)$ is deviated from $\mathbf{d}_3(s)$ by the combined angles $d\theta_1 = \kappa_1 ds$ and $d\theta_2 = \kappa_2 ds$ along ds (fig. 5.5c). Thus, its overall contribution to the balance of moments over $\mathbf{d}_1(s)$ is :

$$Q(s + ds) \cos(\kappa_1 ds) \sin(\kappa_2 ds) = \kappa_2 Q(s) ds + o(ds)$$

5.5 Numerical resolution

5.5.1 Main hypothesis

On néglige les forces d'inertie liées à la rotation de l'élément (devant quoi ?? traitement quasi-statique par rapport à la rotation). Cette hypothèse est faite explicitement chez Florence Bertail :

[CBd13] “neglecting inertial momentum due to the vanishing cross-section lead to the following dynamic equations for a Kirchhoff rod”

Cette hypothèse est faite mais passée sous silence chez Douthe, Adriaenssen, D'Amico lorsqu'ils déduisent l'effort tranchant du moment de flexion.

Principe :

- les équations constitutives permettent le calcul de M_1 , M_2 , Q à partir de la géométrie $\{\mathbf{x}, \theta\}$.
- La seconde loi de kirchhoff projetée sur les axes matériels 1 et 2 de la section me donnent accès aux efforts tranchants T_1 et T_2 .
- La seconde loi de kirchhoff projetée sur les axes matériel 3 (tangente à la centerline) de la section me donnent l'hypothèse quasi-statique de Audoly.

5.5.2 Discret beam model

Lets call : $l_i = \|\mathbf{e}_i\|$ with $i \in [0, n_e]$. Lets call : $u_i = \frac{e_i}{l_i}$ with $i \in [0, n_e]$.

Lets call : $L_i = \|\mathbf{e}_{2i} + \mathbf{e}_{2i+1}\|$ with $i \in [0, n_g]$.

We have : $\mathbf{d}_{3,i+1/2} = \mathbf{u}_i$

Let \mathbf{B}_i be the material stiffness matrix along the principal axes of inertia, uniform over the slice $]\mathbf{x}_{2i}, \mathbf{x}_{2i+2}[$. Thus, it has the following form in the material basis :

$$\mathbf{B}_i = \begin{bmatrix} EI_1 & 0 & 0 \\ 0 & EI_2 & 0 \\ 0 & 0 & GJ \end{bmatrix}_i \quad (5.24)$$

5.5.3 Discret bending moments and curvatures

We assume bending moments and curvatures to be quadratic over $]\mathbf{x}_{2i}, \mathbf{x}_{2i+2}[$.

At ghost vertices

$$\kappa \mathbf{b}_{2i-1} = \frac{2}{L_{i-1}} \mathbf{u}_{2i-2} \times \mathbf{u}_{2i-1} \quad \kappa \mathbf{b}_{2i+1} = \frac{2}{L_i} \mathbf{u}_{2i} \times \mathbf{u}_{2i+1} \quad (5.25)$$

$$\mathbf{t}_{2i-1} = \frac{l_{2i-1}}{L_{i-1}} \mathbf{u}_{2i-2} + \frac{l_{2i-2}}{L_{i-1}} \mathbf{u}_{2i-1} \quad \mathbf{t}_{2i+1} = \frac{l_{2i+1}}{L_i} \mathbf{u}_{2i} + \frac{l_{2i}}{L_i} \mathbf{u}_{2i+1} \quad (5.26)$$

$$\mathbf{t}_{2i}^- = 2(\mathbf{t}_{2i-1} \cdot \mathbf{u}_{2i-1}) \mathbf{u}_{2i-1} - \mathbf{t}_{2i-1} \quad \mathbf{t}_{2i}^+ = 2(\mathbf{t}_{2i+1} \cdot \mathbf{u}_{2i}) \mathbf{u}_{2i} - \mathbf{t}_{2i+1} \quad (5.27)$$

$$\mathbf{t}_{2i} = \frac{\mathbf{t}_{2i}^- + \mathbf{t}_{2i}^+}{\|\mathbf{t}_{2i}^- + \mathbf{t}_{2i}^+\|} \quad (5.28)$$

At handle vertices

Rajouter les conditions aux limites moment nul vs moment prescrit

$$\kappa \mathbf{b}_{2i}^- = \frac{2}{l_{2i-1}} \mathbf{u}_{2i-1} \times \mathbf{t}_{2i} \quad \kappa \mathbf{b}_{2i}^+ = \frac{2}{l_{2i}} \mathbf{t}_{2i} \times \mathbf{u}_{2i} \quad (5.29)$$

$$\mathbf{M}_{2i-1} = \mathbf{B}_{i-1}(\kappa \mathbf{b}_{2i-1} - \overline{\kappa \mathbf{b}_{2i-1}}) \quad (5.30)$$

$$\mathbf{M}_{2i+1} = \mathbf{B}_i(\kappa \mathbf{b}_{2i+1} - \overline{\kappa \mathbf{b}_{2i+1}}) \quad (5.31)$$

$$\mathbf{M}_{2i} = \frac{1}{2} \mathbf{B}_{i-1}(\kappa \mathbf{b}_{2i}^- - \overline{\kappa \mathbf{b}_{2i}^-}) + \frac{1}{2} \mathbf{B}_i(\kappa \mathbf{b}_{2i}^+ - \overline{\kappa \mathbf{b}_{2i}^+}) \quad (5.32)$$

$$\mathbf{M}_{2i}^- = \mathbf{M}_{2i} + \frac{1}{2} \mathbf{M}_{2i}^{ext} \quad (5.33)$$

$$\mathbf{M}_{2i}^+ = \mathbf{M}_{2i} - \frac{1}{2} \mathbf{M}_{2i}^{ext} \quad (5.34)$$

This ensure that the static condition is satisfied at all time : $\mathbf{M}^{ext} + \mathbf{M}^+ - \mathbf{M}^- = 0$

Then, it is possible to give the updated curvatures :

$$\kappa \mathbf{b}_{2i}^- = \mathbf{B}_{i-1}^{-1} \mathbf{M}_{2i}^- + \overline{\kappa \mathbf{b}}_{2i}^- \quad (5.35)$$

$$\kappa \mathbf{b}_{2i}^+ = \mathbf{B}_i^{-1} \mathbf{M}_{2i}^+ + \overline{\kappa \mathbf{b}}_{2i}^+ \quad (5.36)$$

5.5.4 Discret twisting moment

We assume the twisting moment and the rate of twist to vary linearly over $] \mathbf{x}_{2i}, \mathbf{x}_{2i+2}[$. Thus, the rate of twist at mid edge is given by :

$$\tau_{i+1/2} = \frac{\Delta \theta_i}{l_i} \quad (5.37)$$

And $\theta_{i+1} - \theta_i$ is the additional twisting angle between two frames with parallel transport.

$$Q_{i+1/2} = GJ(\tau_{i+1/2} - \bar{\tau}_{i+1/2}) \quad (5.38)$$

5.5.5 Discret axial force

We assume the axial force and the axial strain to vary linearly over $] \mathbf{x}_{2i}, \mathbf{x}_{2i+2}[$. Thus, the axial strain at mid edge is given by :

$$\epsilon_{i+1/2} = \frac{l_i}{\bar{l}_i} - 1 \quad (5.39)$$

$$N_{i+1/2} = ES\epsilon_{i+1/2} \quad (5.40)$$

5.5.6 Discret shear force

Shear forces are computed from the second Kirchhoff law, considering that the inertial term is negligible.

$$\mathbf{F}_{i+1/2} = \mathbf{d}_{3,i+1/2} \times (\mathbf{M}_{i+1/2}' + \mathbf{m}_{ext,i}) + Q_{i+1/2} \kappa \mathbf{b}_{i+1/2} - \tau_{i+1/2} \mathbf{M}_{i+1/2} \quad (5.41)$$

5.5.7 Interpolation

5.6 Conclusion

Remind that the beam is subject to a distributed external force \mathbf{f}_{ext} and a distributed external moment \mathbf{m}_{ext} .

We neglect rotational inertial effects on \mathbf{d}_1 et \mathbf{d}_2 in (5.20b) and (5.20c) which leads to the following shear force :

$$\mathbf{F}^\perp(s) = \mathbf{d}_3 \times (\mathbf{M}' + \boldsymbol{\Omega} \times \mathbf{M} + \mathbf{m}_{ext}) \quad (5.42)$$

$$\mathbf{F}^\parallel(s) = N \mathbf{d}_3 \quad (5.43)$$

We may neglect as well the last term ($\tau \mathbf{M}$) and get back to the shear force obtained by the variational approach. The total internal force acting on the beam is hence given by :

$$\mathbf{F}(s) = \mathbf{N}(s) + \mathbf{T}(s) \quad (5.44)$$

Sections are subject to the following rotational moment around the centerline :

$$\boldsymbol{\Gamma}(s) = Q' + \mathbf{d}_3 \cdot (\kappa \mathbf{b} \times \mathbf{M} + \mathbf{m}_{ext}) \quad (5.45)$$

Bibliography

- [ABW99] Sigrid Adriaenssens, Michael Barnes, and Christopher Williams. A new analytic and numerical basis for the form-finding and analysis of spline and gridshell structures. In B Kumar and B H V Topping, editors, *Computing Developments in Civil and Structural Engineering*, pages 83–91. Civil-Comp Press, Edinburgh, 1999.
- [Ant05] Stuart Antman. *Nonlinear problems of elasticity*. Applied mathematical sciences. Springer, New York, 2005.
- [BAK13] Michael Barnes, Sigrid Adriaenssens, and Meghan Krupka. A novel torsion/bending element for dynamic relaxation modeling. *Computers & Structures*, 119:60–67, apr 2013.
- [Bar99] Michael Barnes. Form Finding and Analysis of Tension Structures by Dynamic Relaxation. *International Journal of Space Structures*, 14(2):89–104, 1999.
- [BEL⁺93] D Bernard, H Ellis, M A I O Lembo, L U Zheng, and Irwin Tobias. On the Dynamics of Rods in the Theory of Kirchhoff and Clebsch. 121:339–359, 1993.
- [CBd13] Romain Casati and Florence Bertails-descoubes. Super space clothoids. In *SIGGRAPH*, 2013.
- [Day65] Alister Day. An Introduction to dynamic relaxation. *The Engineer*, 1965.
- [DBC06] Cyril Douthe, Olivier Baverel, and Jean-François Caron. Formfinding of a grid shell in composite materials. *Journal of the IASS*, 47:53–62, 2006.
- [Dil92] Ellis Harold Dill. Kirchhoff’s theory of rods. *Archive for History of Exact Sciences*, page 23, 1992.
- [DKZ14] B. D’Amico, A. Kermani, and H. Zhang. Form finding and structural analysis of actively bent timber grid shells. *Engineering Structures*, 81:195–207, 2014.
- [DLP13] Ye Duan, Dong Li, and P. Frank Pai. Geometrically exact physics-based modeling and computer animation of highly flexible 1D mechanical systems. *Graphical Models*, 75(2):56–68, 2013.
- [dPTL⁺15] Lionel du Peloux, Frédéric Tayeb, Baptiste Lefevre, Olivier Baverel, and Jean-François Caron. Formulation of a 4-DoF torsion / bending element for the formfinding of elastic gridshells. In *Proceedings of the International Association for Shell and Spatial Structures*, number August, pages 1–14, Amsterdam, 2015.
- [DZK16] B. D’Amico, H. Zhang, and A. Kermani. A finite-difference formulation of elastic rod for the design of actively bent structures. *Engineering Structures*, 117:518–527, 2016.
- [Hoo06] P C J Hoogenboom. 7 Vlasov torsion theory. (October):1–12, 2006.

- [LL09] Holger Lang and Joachim Linn. Lagrangian field theory in space-time for geometrically exact Cosserat rods. 150:21, 2009.
- [MPW14] Christoph Meier, Alexander Popp, and Wolfgang A. Wall. An objective 3D large deformation finite element formulation for geometrically exact curved Kirchhoff rods. *Computer Methods in Applied Mechanics and Engineering*, 278(August):445–478, 2014.
- [Neu09] S. Neukirch. *Enroulement, contact et vibrations de tiges élastiques*. PhD thesis, 2009.
- [Spi08] Jonas Spillmann. *CORDE : Cosserat rod elements for the animation of interacting elastic rods*. PhD thesis, 2008.
- [The07] Adrien Theetten. *Splines dynamiques géométriquement exactes : simulation haute performance et interaction*. PhD thesis, Université des Sciences et Technologies de Lille, 2007.
- [Wak80] David Wakefield. *Dynamic relaxation analysis of pretensioned networks supported by compression arches*. PhD thesis, City University London, 1980.

