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A simplified model for elastic thin shells.

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Abstract. We introduce a simplified model for the minimization of the elastic energy in thin shells. This model is not obtained by an asymptotic analysis. The thickness of the shell remains a parameter as in Reissner-Mindlin's model for plates and Koiter's model for shells in the linear case. The simplified model admits always minimizers by contrast with the original one. We show the relevance of our approach by proving that the minimum of the simplified model and the infimum of the full model have the same limit as the thickness tends to 0.

1. Introduction

This paper is devoted to introduce and justify a simplified model for nonlinear elastic shells. We consider an elastic shell, whose energy is denoted W , submitted to applied forces $f_{\kappa,\delta}$. The total energy given by $J_{\kappa,\delta}(v) = \int_{S \times]-\delta,\delta[} W(E(v)) - \int_{S \times]-\delta,\delta[} f_{\kappa,\delta} \cdot (v - I_d)$ if $\det(\nabla v) > 0$ and where $E(v) = 1/2((\nabla v)^T \nabla v - \mathbf{I}_3)$ is the Green-St Venant's tensor and I_d is the identity map. The Korn's inequalities established in [Note] (see also [ciarlet]) allow us to claim that if the order of $f_{\kappa,\delta}$ is equal to $\delta^{2\kappa-2}$ with $1 \leq \kappa \leq 2$ or δ^κ with $\kappa \geq 2$, then the order of the total energy $J_{\kappa,\delta}(v)$ is at least $\delta^{2\kappa-1}$. We set

$$m_\kappa = \lim_{\delta \rightarrow 0} \frac{m_{\kappa,\delta}}{\delta^{2\kappa-1}}, \quad m_{\kappa,\delta} = \inf_{v \in \mathbf{U}_\delta} J_{\kappa,\delta}(v),$$

where \mathbf{U}_δ is the set of admissible deformations. Even for a classical St-Venant-Kirchhoff material, proving the existence of a minimizer for the above problem is still an open problem. The aim of this paper is to replace the above minimization problem for the functional $J_{\kappa,\delta}$ by an approximate minimization problem for a simplified functional $J_{\kappa,\delta}^s$ defined on a new set \mathbb{D} and which admits minimizers for $\kappa > 1$. The expression and the choice of \mathbb{D} rely on the decomposition technique introduced in [Note]. The order of the total simplified energy $J_{\kappa,\delta}^s(\mathbf{v})$ is also at least $\delta^{2\kappa-1}$. We set

$$m_\kappa^s = \lim_{\delta \rightarrow 0} \frac{m_{\kappa,\delta}^s}{\delta^{2\kappa-1}}, \quad m_{\kappa,\delta}^s = \min_{\mathbf{v} \in \mathbb{D}} J_{\kappa,\delta}^s(\mathbf{v}).$$

Let us just recall that for a shell with mid-surface S and thickness 2δ , a deformation v defined on this shell is decomposed as (see [note])

$$v = \mathcal{V} + s_3 \mathbf{Rn} + \bar{v},$$

where the fields \mathcal{V} and \mathbf{R} are defined on S , s_3 is the variable in the direction \mathbf{n} which is a unit vector field normal to S and \bar{v} is a field still defined on the 3D shell. The matrix \mathbf{R} takes its values in $SO(3)$. The

fields \mathcal{V} , \mathbf{R} and \bar{v} are estimated in terms of the "geometrical energy" $\|\text{dist}(\nabla v, SO(3))\|_{L^2(S\times]-\delta, \delta[)}$ and the thickness of the shell.

We first show that we can approximate the Green-St Venant's strain tensor $E(v) = 1/2((\nabla v)^T \nabla v - \mathbf{I}_3)$ by $(\nabla_x v - \mathbf{R})^T \mathbf{R} + \mathbf{R}^T (\nabla_x v - \mathbf{R})$ as soon as $\|\text{dist}(\nabla v, SO(3))\|_{L^2(S\times]-\delta, \delta[)} = o(\delta^{1/2})$. Secondly, we justify that we can omit the partial derivatives of $\frac{\partial \bar{v}}{\partial s_1}$ and $\frac{\partial \bar{v}}{\partial s_2}$ in the expression of ∇v . Adopting such simplifications leads to a simplified Green-St Venant's strain tensor which involves linearly the first partial derivatives of \mathcal{V} , \mathbf{R} and of $\frac{\partial \bar{v}}{\partial s_3}$. Hence, we introduce the set \mathbb{D}_δ of admissible triples $\mathbf{v} = (\mathcal{V}, \mathbf{R}, \bar{v})$ and we denote by $E(\mathbf{v})$ the simplified Green-St Venant's tensor. Then we introduce the simplified total energy $J_{\kappa, \delta}^s(\mathbf{v})$ as follows. Firstly we replace $\int_{S\times]-\delta, \delta[)} W(E(v))$ by $\int_{S\times]-\delta, \delta[)} Q(E(\mathbf{v}))$ where Q is the quadratic form which approximate W near the origin. Secondly we add two penalization terms in order to approximate the usual limit kinematic condition $\frac{\partial \mathcal{V}}{\partial s_\alpha} = \mathbf{R}t_\alpha$ and to insure the coerciveness of $J_{\kappa, \delta}^s$. Finally in the term involving the forces we neglect the contribution of the warping \bar{v} . As announced above we prove that $J_{\kappa, \delta}^s$ admit minimizers on \mathbb{D}_δ . A natural way to justify the approximation process described above is to show that $m_\kappa^s = m_\kappa$. In the present paper we established this result for $\kappa = 2$.

In this spirit, the introduction of $J_{\kappa, \delta}^s$ is a nonlinear version of the approach which leads to the simplified Timoshenko's model for rods, the Reisner-Mindlin's model for plates and the Koiter's model for shells in linear elasticity.

As general references on the theory of nonlinear elasticity, we refer to [1], [6] and [22] and to the extensive bibliographies of these works. For the justification of plates or shell models in nonlinear elasticity we refer to [7], [8], [9], [11], [12], [15], [19], [21], [23], [24]. The derivation of limit energies for thin domains using Γ -convergence arguments are developed in [14], [15], [20], [21]. The decomposition of the deformations in thin structures is introduced in [17], [18] and a few applications to the junctions of multi-structures and homogenization are given in [2], [3], [4]. The justification of simplified models for rods and plates in linear elasticity, based on a decomposition technique of the displacement, is presented in [GG1], [GG2]. In this linear case, error estimates between the solution of the initial model and the one of the simplified model are also established. In some sense, these works give a mathematical justification of Timoshenko's model for rods and Reisner-Mindlin's model for plates.

The paper is organized as follows. Section 2 is devoted to describe the geometry of the shell and to give a few notations. In Section 3 we recall the results of [BGC]: decomposition of a deformation of a thin shell, estimates on the terms of this decomposition and two nonlinear Korn's inequalities. Section 4 is concerned with a standard rescaling. We present the simplification of the Green-St Venant's strain tensor of a deformation in Section 5. We also introduce the set \mathbb{D} of admissible triples $\mathbf{v} = (\mathcal{V}, \mathbf{R}, \bar{V})$, defined on the fixed domain $S\times]-1, 1[$, and we prove Korn's type inequalities for the elements of \mathbb{D} (see Proposition 5.1). In Section 6 we consider nonlinear elastic shells and we use the results of [BGC] to scale the applied forces in order to obtain a priori estimates on $m_{\kappa, \delta}$. Section 7 is devoted to introduce the simplified elastic model for shells and to prove the existence of minimizers for the rescaled energy $J_{\kappa, \delta}^s$. In Section 8 and the following ones, we restrict the analysis to $\kappa = 2$. We first prove that if $(\mathbf{v}_\delta) \subset \mathbb{D}$ is a sequence of minimizers for $J_{\kappa, \delta}^s(\cdot)$, then, up to a subsequence, \mathbf{v}_δ converges to a minimizer $\mathbf{v} \in \mathbb{D}$ of a limit functional whose minimum is equal to m_2^s . In Section 9 we prove the main result of this paper namely that $m_2 = m_2^s$ which is a justification of the analysis of the previous sections. We give an alternative formulation of the simplified problem for $J_{\kappa, \delta}^s$ through elimination of the variable \bar{V} . At last an appendix contains an approximation result for the elements of \mathbb{D} and an algebraic elimination process for quadratic forms.

2. The geometry and notations.

Let us introduce a few notations and definitions concerning the geometry of the shell (see [17] for a detailed presentation).

Let ω be a bounded domain in \mathbb{R}^2 with lipschitzian boundary and let ϕ be an injective mapping from $\bar{\omega}$ into \mathbb{R}^3 of class \mathcal{C}^2 . We denote S the surface $\phi(\bar{\omega})$. We assume that the two vectors $\frac{\partial\phi}{\partial s_1}(s_1, s_2)$ and $\frac{\partial\phi}{\partial s_2}(s_1, s_2)$ are linearly independent at each point $(s_1, s_2) \in \bar{\omega}$.

We set

$$(2.1) \quad \mathbf{t}_1 = \frac{\partial\phi}{\partial s_1}, \quad \mathbf{t}_2 = \frac{\partial\phi}{\partial s_2}, \quad \mathbf{n} = \frac{\mathbf{t}_1 \wedge \mathbf{t}_2}{\|\mathbf{t}_1 \wedge \mathbf{t}_2\|_2}.$$

The vectors \mathbf{t}_1 and \mathbf{t}_2 are tangential vectors to the surface S and the vector \mathbf{n} is a unit normal vector to this surface. The reference fiber of the shell is the segment $] -\delta, \delta[$. We set

$$\Omega_\delta = \omega \times] -\delta, \delta[.$$

Now we consider the mapping $\Phi : \bar{\omega} \times \mathbb{R} \longrightarrow \mathbb{R}^3$ defined by

$$(2.2) \quad \Phi : (s_1, s_2, s_3) \longmapsto x = \phi(s_1, s_2) + s_3 \mathbf{n}(s_1, s_2).$$

There exists $\delta_0 \in (0, 1]$ depending only on S , such that the restriction of Φ to the compact set $\bar{\Omega}_{\delta_0} = \bar{\omega} \times [-\delta_0, \delta_0]$ is a \mathcal{C}^1 -diffeomorphism of that set onto its range (see e.g. [8]). Hence, there exist two constants $c_0 > 0$ and $c_1 \geq c_0$, which depend only on ϕ , such that

$$(2.3) \quad \forall \delta \in (0, \delta_0], \quad \forall s \in \Omega_{\delta_0}, \quad c_0 \leq \|\|\nabla_s \Phi(s)\|\| \leq c_1, \quad \text{and for } x = \Phi(s) \quad c_0 \leq \|\|\nabla_x \Phi^{-1}(x)\|\| \leq c_1.$$

Definition 2.1. For $\delta \in (0, \delta_0]$, the shell \mathcal{Q}_δ is defined as follows:

$$\mathcal{Q}_\delta = \Phi(\Omega_\delta).$$

The mid-surface of the shell is S . The lateral boundary of the shell is $\Gamma_\delta = \Phi(\partial\omega \times] -\delta, \delta[)$. The fibers of the shell are the segments $\Phi(\{(s_1, s_2)\} \times] -\delta, \delta[)$, $(s_1, s_2) \in \omega$. We respectively denote by x and s the running points of \mathcal{Q}_δ and of Ω_δ . A function v defined on \mathcal{Q}_δ can be also considered as a function defined on Ω_δ that we will also denote by v . As far as the gradients of v are concerned we have $\nabla_x v$ and $\nabla_s v = \nabla_x v \cdot \nabla \Phi$ and e.g. for a.e. $x = \Phi(s)$

$$c \|\|\nabla_x v(x)\|\| \leq \|\|\nabla_s v(s)\|\| \leq C \|\|\nabla_x v(x)\|\|,$$

where the constants are strictly positive and do not depend on δ .

Since we will need to extend a deformation defined over the shell \mathcal{Q}_δ , we also assume the following.

For any $\eta > 0$, let us first denote the open set

$$\omega_\eta = \{(s_1, s_2) \in \mathbb{R}^2 \mid \text{dist}((s_1, s_2), \omega) < \eta\}.$$

We assume that there exist $\eta_0 > 0$ and an extension of the mapping ϕ (still denoted ϕ) belonging to $(\mathcal{C}^2(\bar{\omega}_{\eta_0}))^3$ which remains injective and such that the vectors $\frac{\partial\phi}{\partial s_1}(s_1, s_2)$ and $\frac{\partial\phi}{\partial s_2}(s_1, s_2)$ are linearly independent at each point $(s_1, s_2) \in \bar{\omega}_{\eta_0}$. The function Φ (introduced above) is now defined on $\bar{\omega}_{\eta_0} \times [-\delta_0, \delta_0]$ and we still

assume that it is a \mathcal{C}^1 - diffeomorphism of that set onto its range. Then there exist four constants c'_0, c'_1, c' and C' such that

$$(2.4) \quad \begin{cases} \forall s \in \bar{\omega}_{n_0} \times [-\delta_0, \delta_0], & c'_0 \leq |||\nabla_s \Phi(s)||| \leq c'_1, \text{ and for } x = \Phi(s) \quad c'_0 \leq |||\nabla_x \Phi^{-1}(x)||| \leq c'_1 \\ c' |||\nabla_x v(x)||| \leq |||\nabla_s v(s)||| \leq C' |||\nabla_x v(x)|||, & \text{for a.e. } x = \Phi(s). \end{cases}$$

At the end we denote by I_d the identity map of \mathbb{R}^3 .

Notation. We denote x the running point of \mathcal{Q}_δ . The running point of the domain Ω_δ is s . A function v defined on \mathcal{Q}_δ can be also considered as a function defined on Ω_δ that we will also denote by v . As far as the gradients of v is concerned we have $\nabla_x v$ and $\nabla_s v = \nabla_x v \cdot \nabla \Phi$ and e.g. for a.e. $x = \Phi(s)$

$$c |||\nabla_x v(x)||| \leq |||\nabla_s v(s)||| \leq C |||\nabla_x v(x)|||,$$

where the constants are strictly positive and do not depend on δ .

3. Decomposition of a deformation.

We recall first below a theorem of decomposition of the deformations established in [BGC] (Theorem 3.4 of Section 3).

Theorem 3.4. *There exists a constant $C(S)$ which depends only on the mid-surface of the shell such that for all deformation v belonging to $(H^1(\mathcal{Q}_\delta))^3$ and satisfying*

$$(3.1) \quad |||dist(\nabla_x v, SO(3))|||_{L^2(\mathcal{Q}_\delta)} \leq C(S)\delta^{3/2},$$

then, there exist $\mathcal{V} \in (H^1(\omega))^3$, $\mathbf{R} \in (H^1(\omega))^{3 \times 3}$ satisfying $\mathbf{R}(s_1, s_2) \in SO(3)$ for a.e. $(s_1, s_2) \in \omega$ and \bar{V} belonging to $(H^1(\mathcal{Q}_\delta))^3$ such that for a.e. $s \in \Omega_\delta$ and a.e. $(s_1, s_2) \in \omega$

$$(3.2) \quad v(s) = \mathcal{V}(s_1, s_2) + s_3 \mathbf{R}(s_1, s_2) \mathbf{n}(s_1, s_2) + \bar{v}(s), \quad \left(\mathcal{V}(s_1, s_2) = \frac{1}{2\delta} \int_{-\delta}^{\delta} v(s_1, s_2, t) dt \right)$$

with the following estimates

$$(3.3) \quad \begin{cases} |||\bar{v}|||_{(L^2(\Omega_\delta))^3} \leq C\delta |||dist(\nabla_x v, SO(3))|||_{L^2(\mathcal{Q}_\delta)} \\ |||\nabla_s \bar{v}|||_{(L^2(\Omega_\delta))^9} \leq C |||dist(\nabla_x v, SO(3))|||_{L^2(\mathcal{Q}_\delta)} \\ \left\| \frac{\partial \mathbf{R}}{\partial s_\alpha} \right\|_{(L^2(\omega))^9} \leq \frac{C}{\delta^{3/2}} |||dist(\nabla_x v, SO(3))|||_{L^2(\mathcal{Q}_\delta)} \\ \left\| \frac{\partial \mathcal{V}}{\partial s_\alpha} - \mathbf{R} \mathbf{t}_\alpha \right\|_{(L^2(\omega))^3} \leq \frac{C}{\delta^{1/2}} |||dist(\nabla_x v, SO(3))|||_{L^2(\mathcal{Q}_\delta)} \\ |||\nabla_x v - \mathbf{R}|||_{(L^2(\Omega_\delta))^9} \leq C |||dist(\nabla_x v, SO(3))|||_{L^2(\mathcal{Q}_\delta)} \end{cases}$$

where the constant C does not depend on δ .

Let us now precise the boundary conditions. To this end, let γ_0 be an open subset of $\partial\omega$ which made of a finite number of connected components (whose closure are disjoint), we set

$$\Gamma_{0,\delta} = \Phi(\gamma_0 \times]-\delta, \delta[),$$

We adopt the following boundary condition

$$v(x) = x \quad \text{on } \Gamma_{0,\delta}.$$

Indeed, we have

$$(3.4) \quad \mathcal{V} = \phi \quad \text{on} \quad \gamma_0.$$

Moreover due to Lemma 4.1 of [BGCoques], we can choose \mathbf{R} and \bar{v} in Theorem 3.4 above such that

$$(3.5) \quad \mathbf{R} = \mathbf{I}_3 \quad \text{on} \quad \gamma_0, \quad \bar{v} = 0 \quad \text{on} \quad \Gamma_{0,\delta}.$$

In any case, under the above boundary conditions, we have by Theorem 4.2 of [BGCoques] the following nonlinear Korn's inequalities

$$(3.6) \quad \begin{cases} \|v - I_d\|_{(L^2(\mathcal{Q}_\delta))^3} + \|\nabla_x v - \mathbf{I}_3\|_{(L^2(\mathcal{Q}_\delta))^9} \leq C(\delta^{1/2} + \|\text{dist}(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}), \\ \|(v - I_d) - (\mathcal{V} - \phi)\|_{(L^2(\mathcal{Q}_\delta))^3} \leq C\delta(\delta^{1/2} + \|\text{dist}(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}), \end{cases}$$

and

$$(3.7) \quad \begin{cases} \|v - I_d\|_{(L^2(\mathcal{Q}_\delta))^3} + \|\nabla_x v - \mathbf{I}_3\|_{(L^2(\mathcal{Q}_\delta))^9} \leq \frac{C}{\delta} \|\text{dist}(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}, \\ \|(v - I_d) - (\mathcal{V} - \phi)\|_{(L^2(\mathcal{Q}_\delta))^3} \leq C \|\text{dist}(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}. \end{cases}$$

Inequalities (3.6) are better than those (3.7) if the order of the geometric energy $\|\text{dist}(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}$ is greater than $\delta^{3/2}$.

4. Rescaling Ω_δ

As [BGCoques], we rescale Ω_δ using the operator

$$(\Pi_\delta w)(s_1, s_2, S_3) = w(s_1, s_2, \delta S_3) \text{ for any } (s_1, s_2, S_3) \in \Omega$$

defined for e.g. $w \in L^2(\Omega_\delta)$ for which $(\Pi_\delta w) \in L^2(\Omega)$. Let v be a deformation decomposed as (3.2), by transforming by Π_δ we obtain

$$\Pi_\delta(v)(s_1, s_2, S_3) = \mathcal{V}(s_1, s_2) + \delta S_3 \mathbf{R}(s_1, s_2) \mathbf{n}(s_1, s_2) + \Pi_\delta(\bar{v})(s_1, s_2, S_3), \quad \text{for a.e. } (s_1, s_2, S_3) \in \Omega.$$

The estimates (3.3) of \bar{v} transposed over Ω are (notice that $\Pi_\delta\left(\frac{\partial \bar{v}}{\partial s_3}\right) = \frac{1}{\delta} \frac{\partial \Pi_\delta(\bar{v})}{\partial S_3}$)

$$(4.1) \quad \begin{cases} \|\Pi_\delta(\bar{v})\|_{(L^2(\Omega))^3} \leq C\delta^{1/2} \|\text{dist}(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)} \\ \left\| \frac{\partial \Pi_\delta(\bar{v})}{\partial s_1} \right\|_{(L^2(\Omega))^3} \leq \frac{C}{\delta^{1/2}} \|\text{dist}(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)} \\ \left\| \frac{\partial \Pi_\delta(\bar{v})}{\partial s_2} \right\|_{(L^2(\Omega))^3} \leq \frac{C}{\delta^{1/2}} \|\text{dist}(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)} \\ \left\| \frac{\partial \Pi_\delta(\bar{v})}{\partial S_3} \right\|_{(L^2(\Omega))^3} \leq C\delta^{1/2} \|\text{dist}(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}, \end{cases}$$

5. Simplification in the Green-St Venant's strain tensor.

In this section we define a simplified local energy. Let v be a deformation of the shell belonging to $(H^1(\mathcal{Q}_\delta))^3$ and satisfying the condition (3.1). We decompose v as (3.2). We have the identity

$$(\nabla_x v)^T \nabla_x v - \mathbf{I}_3 = (\nabla_x v - \mathbf{R})^T \mathbf{R} + \mathbf{R}^T (\nabla_x v - \mathbf{R}) + (\nabla_x v - \mathbf{R})^T (\nabla_x v - \mathbf{R}).$$

Thanks to estimates (3.3) we get

$$(5.1) \quad \begin{cases} \|\Pi_\delta((\nabla_x v - \mathbf{R})^T \mathbf{R} + \mathbf{R}^T (\nabla_x v - \mathbf{R}))\|_{(L^2(\Omega))^{3 \times 3}} \leq C \frac{\|dist(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}}{\delta^{1/2}}, \\ \|\Pi_\delta((\nabla_x v - \mathbf{R})^T (\nabla_x v - \mathbf{R}))\|_{(L^1(\Omega))^{3 \times 3}} \leq C \left[\frac{\|dist(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}}{\delta^{1/2}} \right]^2. \end{cases}$$

In view of (3.1), these estimates show that the term $\Pi_\delta((\nabla_x v - \mathbf{R})^T (\nabla_x v - \mathbf{R}))$ can be neglected in the Green-St Venant's strain tensor.

Now we have

$$\frac{\partial v}{\partial s_1} = \nabla_x v (\mathbf{t}_1 + s_3 \frac{\partial \mathbf{n}}{\partial s_1}), \quad \frac{\partial v}{\partial s_2} = \nabla_x v (\mathbf{t}_2 + s_3 \frac{\partial \mathbf{n}}{\partial s_2}), \quad \frac{\partial v}{\partial s_3} = \nabla_x v \mathbf{n}.$$

Then

$$(\nabla_x v - \mathbf{R}) (\mathbf{t}_\alpha + s_3 \frac{\partial \mathbf{n}}{\partial s_\alpha}) = \left(\frac{\partial \mathcal{V}}{\partial s_\alpha} - \mathbf{R} \mathbf{t}_\alpha \right) + s_3 \frac{\partial \mathbf{R}}{\partial s_\alpha} \mathbf{n} + \frac{\partial \bar{v}}{\partial s_\alpha}, \quad (\nabla_x v - \mathbf{R}) \mathbf{n} = \frac{\partial \bar{v}}{\partial s_3}.$$

As a consequence of the above equalities and the following estimates (obtained from (3.3) and (4.1)):

$$(5.2) \quad \begin{cases} \left\| \frac{\partial \mathcal{V}}{\partial s_\alpha} - \mathbf{R} \mathbf{t}_\alpha \right\|_{(L^2(\Omega))^3} \leq C \frac{\|dist(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}}{\delta^{1/2}}, \\ \left\| \Pi_\delta \left(s_3 \frac{\partial \mathbf{R}}{\partial s_\alpha} \mathbf{n} \right) \right\|_{(L^2(\Omega))^3} \leq C \frac{\|dist(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}}{\delta^{1/2}}, \\ \left\| \Pi_\delta \left(\frac{\partial \bar{v}}{\partial s_3} \right) \right\|_{(L^2(\Omega))^3} \leq C \frac{\|dist(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}}{\delta^{1/2}}, \\ \left\| \Pi_\delta \left(\frac{\partial \bar{v}}{\partial s_\alpha} \right) \right\|_{(H^{-1}(\Omega))^3} \leq C \delta \left[\frac{\|dist(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}}{\delta^{1/2}} \right] \end{cases}$$

we deduce that in the quantity $(\nabla_x v - \mathbf{R})^T \mathbf{R} + \mathbf{R}^T (\nabla_x v - \mathbf{R})$ we can neglect the terms $\frac{\partial \bar{v}}{\partial s_\alpha}$ (due to (3.1) again). We can also neglect the term $s_3 \frac{\partial \mathbf{n}}{\partial s_\alpha}$ which is of order δ .

Now, if in the Green-St Venant's strain tensor of v we carry out the simplifications mentioned above, we are brought to replace

$$\frac{1}{2} \Pi_\delta((\nabla_x v)^T \nabla_x v - \mathbf{I}_3) \quad \text{by} \quad (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} E_\delta(v) (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}$$

where the symmetric matrix $E_\delta(v) \in (L^2(\Omega))^{3 \times 3}$ is equal to

$$(5.3) \quad E_\delta(v) = \begin{pmatrix} \delta S_3 \Gamma_{11}(\mathbf{R}) + \mathcal{Z}_{11} & \delta S_3 \Gamma_{12}(\mathbf{R}) + \mathcal{Z}_{12} & \frac{1}{2\delta} \frac{\partial \bar{V}}{\partial S_3} \cdot \mathbf{t}_1 + \frac{1}{2} \mathcal{Z}_{31} \\ * & \delta S_3 \Gamma_{22}(\mathbf{R}) + \mathcal{Z}_{22} & \frac{1}{2\delta} \frac{\partial \bar{V}}{\partial S_3} \cdot \mathbf{t}_2 + \frac{1}{2} \mathcal{Z}_{32} \\ * & * & \frac{1}{\delta} \frac{\partial \bar{V}}{\partial S_3} \cdot \mathbf{n} \end{pmatrix}$$

$$\Gamma_{\alpha\beta}(\mathbf{R}) = \frac{1}{2} \left[\frac{\partial \mathbf{R}}{\partial s_\alpha} \mathbf{n} \cdot \mathbf{R} \mathbf{t}_\beta + \frac{\partial \mathbf{R}}{\partial s_\beta} \mathbf{n} \cdot \mathbf{R} \mathbf{t}_\alpha \right],$$

$$\mathcal{Z}_{\alpha\beta} = \frac{1}{2} \left[\left(\frac{\partial \mathcal{V}}{\partial s_\alpha} - \mathbf{R} \mathbf{t}_\alpha \right) \cdot \mathbf{R} \mathbf{t}_\beta + \left(\frac{\partial \mathcal{V}}{\partial s_\beta} - \mathbf{R} \mathbf{t}_\beta \right) \cdot \mathbf{R} \mathbf{t}_\alpha \right], \quad \mathcal{Z}_{3\alpha} = \frac{\partial \mathcal{V}}{\partial s_\alpha} \cdot \mathbf{R} \mathbf{n},$$

where $\bar{V} = \mathbf{R}^T \Pi_\delta(\bar{v})$ and where $(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})$ denotes the 3×3 matrix with first column \mathbf{t}_1 , second column \mathbf{t}_2 and third column \mathbf{n} and where $(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} = ((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1})^T$.

Now, we introduce the closed subset \mathbb{D} of $(H^1(\omega))^3 \times (H^1(\omega))^{3 \times 3} \times (L^2(\omega; H^1(-1, 1)))^3$

$$\mathbb{D} = \left\{ \mathbf{v} = (\mathcal{V}, \mathbf{R}, \bar{V}) \in (H^1(\omega))^3 \times (H^1(\omega))^{3 \times 3} \times (L^2(\omega; H^1(-1, 1)))^3 \mid \right. \\ \left. \begin{aligned} \mathbf{R}(s_1, s_2) \in SO(3), \quad \int_{-1}^1 \bar{V}(s_1, s_2, S_3) dS_3 = 0, \\ \int_{-1}^1 S_3 \bar{V}(s_1, s_2, S_3) \mathbf{t}_\alpha dS_3 = 0, \text{ for a.e. } (s_1, s_2) \in \omega, \quad \alpha = 1, 2. \end{aligned} \right\}$$

In \mathbb{D} the last condition on \bar{V} is not imposed to $\Pi_\delta(\bar{v})$, loosely speaking this new condition will allow to decouple the estimates of \bar{V} and $\mathcal{Z}_{i\alpha}$ (see the proof of Proposition 5.1).

For any $\mathbf{v} \in \mathbb{D}$, we consider v defined by

$$\begin{aligned} v(s) &= \mathcal{V}(s_1, s_2) + \mathbf{R}(s_1, s_2) \left[s_3 \mathbf{n}(s_1, s_2) + \bar{V} \left(s_1, s_2, \frac{s_3}{\delta} \right) \right], \quad \text{for a.e. } s \in \Omega_\delta \\ &= \mathcal{V}(s_1, s_2) + s_3 \mathbf{R}(s_1, s_2) \mathbf{n}(s_1, s_2) + \bar{v}(s), \end{aligned}$$

and we set

$$(5.4) \quad \widehat{E}_\delta(\mathbf{v}) = E_\delta(v), \quad \widehat{E}_\delta(\mathbf{v}) \in (L^2(\Omega))^{3 \times 3}.$$

Let us point out that if a triple \mathbf{v} satisfies the limit kinematic condition $\frac{\partial \mathcal{V}}{\partial s_\alpha} = \mathbf{Rt}_\alpha$, then it is easy to obtain

$$\frac{1}{\delta^2} \|\bar{V}\|_{(L^2(\omega; H^1(-1, 1)))^3} + \left\| \frac{\partial \mathbf{R}}{\partial s_\alpha} \right\|_{(L^2(\omega))^{3 \times 3}} \leq \frac{C}{\delta} \|\widehat{E}_\delta(\mathbf{v})\|_{(L^2(\Omega))^{3 \times 3}}$$

which permit with some boundary conditions to control the product norm of \mathbf{v} in term of $\|\widehat{E}_\delta(\mathbf{v})\|_{(L^2(\Omega))^{3 \times 3}}$ and δ . In order to define an energy which have this property for any $\mathbf{v} \in \mathbb{D}$, we are lead to add two penalization terms, which vanish as $\delta \rightarrow 0$, to $\|\widehat{E}_\delta(\mathbf{v})\|_{(L^2(\Omega))^{3 \times 3}}^2$. This is why for every deformation $\mathbf{v} \in \mathbb{D}$ we set

$$(5.5) \quad \mathcal{E}_\delta(\mathbf{v}) = \|\widehat{E}_\delta(\mathbf{v})\|_{(L^2(\Omega))^{3 \times 3}}^2 + \delta^2 \left\| \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{t}_2 - \frac{\partial \mathbf{R}}{\partial s_2} \mathbf{t}_1 \right\|_{(L^2(\omega))^3}^2 + \left\| \frac{\partial \mathcal{V}}{\partial s_1} \cdot \mathbf{Rt}_2 - \frac{\partial \mathcal{V}}{\partial s_2} \cdot \mathbf{Rt}_1 \right\|_{L^2(\omega)}^2.$$

Proposition 5.1. *There exists a positive constant C which does not depend on δ such that for all $\mathbf{v} \in \mathbb{D}$*

$$\frac{1}{\delta^4} \|\bar{V}\|_{(L^2(\omega; H^1(-1, 1)))^3}^2 + \left\| \frac{\partial \mathbf{R}}{\partial s_\alpha} \right\|_{(L^2(\omega))^{3 \times 3}}^2 + \frac{1}{\delta^2} \left\| \frac{\partial \mathcal{V}}{\partial s_\alpha} - \mathbf{Rt}_\alpha \right\|_{(L^2(\omega))^3}^2 \leq \frac{C}{\delta^2} \mathcal{E}_\delta(\mathbf{v}).$$

Proof. First of all there exists a positive constant C independent of δ such that

$$(5.6) \quad \left\{ \begin{aligned} & \delta \left\| \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{n} \cdot \mathbf{Rt}_1 \right\|_{L^2(\omega)} + \delta \left\| \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{n} \cdot \mathbf{Rt}_2 + \frac{\partial \mathbf{R}}{\partial s_2} \mathbf{n} \cdot \mathbf{Rt}_1 \right\|_{L^2(\omega)} + \delta \left\| \frac{\partial \mathbf{R}}{\partial s_2} \mathbf{n} \cdot \mathbf{Rt}_2 \right\|_{L^2(\omega)} \\ & + \|\mathcal{Z}_{11}\|_{L^2(\omega)} + \|\mathcal{Z}_{12}\|_{L^2(\omega)} + \|\mathcal{Z}_{22}\|_{L^2(\omega)} + \left\| \frac{1}{\delta} \frac{\partial \bar{V}}{\partial S_3} \cdot \mathbf{t}_1 + \mathcal{Z}_{31} \right\|_{L^2(\Omega)} \\ & + \left\| \frac{1}{\delta} \frac{\partial \bar{V}}{\partial S_3} \cdot \mathbf{t}_2 + \mathcal{Z}_{32} \right\|_{L^2(\Omega)} + \left\| \frac{1}{\delta} \frac{\partial \bar{V}}{\partial S_3} \cdot \mathbf{n} \right\|_{L^2(\Omega)} \leq C \|\widehat{E}_\delta(\mathbf{v})\|_{(L^2(\Omega))^{3 \times 3}}. \end{aligned} \right.$$

We use the definition of \mathbb{D} to estimate the field $\bar{V} \cdot \mathbf{t}_\alpha$. Introducing the function $\frac{1}{\delta} \bar{V} \cdot \mathbf{t}_\alpha + S_3 \mathcal{Z}_{3\alpha}$, using Poincaré-Wirtinger's inequality and the first condition on \bar{V} in \mathbb{D} give

$$\left\| \frac{1}{\delta} \bar{V} \cdot \mathbf{t}_\alpha + S_3 \mathcal{Z}_{3\alpha} \right\|_{L^2(\Omega)} + \left\| \frac{1}{\delta} \bar{V} \cdot \mathbf{n} \right\|_{L^2(\Omega)} \leq C \|\widehat{E}_\delta(\mathbf{v})\|_{(L^2(\Omega))^{3 \times 3}}.$$

Now we use the second condition on $\bar{\mathbf{V}} \cdot \mathbf{t}_\alpha$ to get the estimates on $\bar{\mathbf{V}}$ and $\mathcal{Z}_{3\alpha}$

$$\sum_{\alpha=1}^2 \left\{ \|\bar{\mathbf{V}} \cdot \mathbf{t}_\alpha\|_{L^2(\omega; H^1(-1,1))} + \delta \|\mathcal{Z}_{3\alpha}\|_{L^2(\omega)} \right\} + \|\bar{\mathbf{V}} \cdot \mathbf{n}\|_{L^2(\omega; H^1(-1,1))} \leq C\delta \|\widehat{\mathcal{E}}_\delta(\mathbf{v})\|_{(L^2(\Omega))^{3 \times 3}}.$$

There exist two antisymmetric matrices \mathbf{A}_1 and \mathbf{A}_2 in $(L^2(\Omega))^{3 \times 3}$ these matrices satisfy

$$\frac{\partial \mathbf{R}}{\partial s_1} = \mathbf{R} \mathbf{A}_1 \quad \frac{\partial \mathbf{R}}{\partial s_2} = \mathbf{R} \mathbf{A}_2.$$

From (5.6) we get

$$\|\mathbf{A}_1 \mathbf{n} \cdot \mathbf{t}_1\|_{L^2(\omega)} + \|\mathbf{A}_1 \mathbf{n} \cdot \mathbf{t}_2 + \mathbf{A}_2 \mathbf{n} \cdot \mathbf{t}_1\|_{L^2(\omega)} + \|\mathbf{A}_2 \mathbf{n} \cdot \mathbf{t}_2\|_{L^2(\omega)} \leq \frac{C}{\delta} \|\widehat{\mathcal{E}}_\delta(\mathbf{v})\|_{(L^2(\Omega))^{3 \times 3}}.$$

Besides there exists a positive constant such that for all antisymmetric matrices $\mathbf{A}_1, \mathbf{A}_2$ we have

$$\begin{aligned} & \|\mathbf{A}_1\|_{(L^2(\omega))^{3 \times 3}} + \|\mathbf{A}_2\|_{(L^2(\omega))^{3 \times 3}} \\ & \leq C \left\{ \|\mathbf{A}_1 \mathbf{n} \cdot \mathbf{t}_1\|_{L^2(\omega)} + \|\mathbf{A}_1 \mathbf{n} \cdot \mathbf{t}_2 + \mathbf{A}_2 \mathbf{n} \cdot \mathbf{t}_1\|_{L^2(\omega)} + \|\mathbf{A}_2 \mathbf{n} \cdot \mathbf{t}_2\|_{L^2(\omega)} + \|\mathbf{A}_1 \mathbf{t}_2 - \mathbf{A}_2 \mathbf{t}_1\|_{(L^2(\omega))^3} \right\}. \end{aligned}$$

Hence we get

$$\left\| \frac{\partial \mathbf{R}}{\partial s_1} \right\|_{(L^2(\omega))^{3 \times 3}} + \left\| \frac{\partial \mathbf{R}}{\partial s_2} \right\|_{(L^2(\omega))^{3 \times 3}} \leq C \left\{ \frac{1}{\delta} \|\widehat{\mathcal{E}}_\delta(\mathbf{v})\|_{(L^2(\Omega))^{3 \times 3}} + \left\| \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{t}_2 - \frac{\partial \mathbf{R}}{\partial s_2} \mathbf{t}_1 \right\|_{(L^2(\omega))^3} \right\}.$$

Due to the estimates concerning the $\mathcal{Z}_{i\alpha}$ we obtain

$$\left\| \frac{\partial \mathcal{V}}{\partial s_\alpha} - \mathbf{R} \mathbf{t}_\alpha \right\|_{(L^2(\omega))^3}^2 \leq C \mathcal{E}_\delta(\mathbf{v}).$$

□

We define now the set of the admissible triples

$$\mathbb{D}_{\gamma_0} = \left\{ \mathbf{v} = (\mathcal{V}, \mathbf{R}, \bar{\mathbf{V}}) \in \mathbb{D} \mid \mathcal{V} = \phi, \mathbf{R} = \mathbf{I}_3 \text{ on } \gamma_0 \right\}.$$

Notice that the triple $\mathbf{I}_d = (\phi, \mathbf{I}_3, 0)$ belongs to \mathbb{D}_{γ_0} and it is associated by (5.4) to the deformation I_d .

In somme sense, the following corollary gives two Korn's inequalities on the set \mathbb{D}_{γ_0} with respect to the quantity $\mathcal{E}_\delta(\mathbf{v})$, the more accurate of which depending on the order of $\mathcal{E}_\delta(\mathbf{v})$.

Corollary 5.2. *There exists a positive constant C which does not depend on δ such that for all $\mathbf{v} \in \mathbb{D}_{\gamma_0}$*

$$\begin{aligned} & \|\mathcal{V} - \phi\|_{(H^1(\omega))^3}^2 + \|\mathbf{R} - \mathbf{I}_3\|_{(H^1(\omega))^{3 \times 3}}^2 \leq \frac{C}{\delta^2} \mathcal{E}_\delta(\mathbf{v}) \\ \text{or} & \|\mathcal{V} - \phi\|_{(H^1(\omega))^3}^2 + \|\mathbf{R} - \mathbf{I}_3\|_{(H^1(\omega))^{3 \times 3}}^2 \leq C(1 + \mathcal{E}_\delta(\mathbf{v})). \end{aligned}$$

Proof. Recall that $\mathbf{R} = \mathbf{I}_3$ and $\mathcal{V} = \phi$ on γ_0 , then from Proposition 5.1 we obtain

$$\|\mathbf{R} - \mathbf{I}_3\|_{(H^1(\omega))^{3 \times 3}}^2 \leq \frac{C}{\delta^2} \mathcal{E}_\delta(\mathbf{v}).$$

Using the above estimate and again Proposition 5.1 we obtain the first estimate on $\mathcal{V} - \phi$. To obtain the second estimate on $\mathcal{V} - \phi$, notice that $\|\mathbf{R} - \mathbf{I}_3\|_{(L^2(\omega))^{3 \times 3}}^2 \leq C$. □

6. Elastic shells

In this section we consider a shell made of an elastic material. Its thickness 2δ is fixed and belongs to $]0, 2\delta_0]$. The local energy $W : \mathbf{S}_3 \rightarrow \mathbb{R}^+$ is a continuous function of symmetric matrices which satisfies the following assumptions which are similar to those adopted in [14], [15] and [16] (the reader is also referred to [6] for general introduction to elasticity)

$$(6.1) \quad \exists c > 0 \quad \text{such that} \quad \forall E \in \mathbf{S}_3 \quad W(E) \geq c \|E\|^2,$$

$$(6.2) \quad \forall \varepsilon > 0, \quad \exists \theta > 0, \quad \text{such that} \quad \forall E \in \mathbf{S}_3 \quad \|E\| \leq \theta \implies |W(E) - Q(E)| \leq \varepsilon \|E\|^2,$$

where Q is a positive quadratic form defined on the set of 3×3 symmetric matrices. Remark that Q satisfies (6.1) with the same constant c .

Still following [6], for any 3×3 matrix F , we set

$$(6.3) \quad \widehat{W}(F) = \begin{cases} W\left(\frac{1}{2}(F^T F - \mathbf{I}_3)\right) & \text{if } \det(F) > 0 \\ +\infty & \text{if } \det(F) \leq 0. \end{cases}$$

Remark that due to (6.1), (6.3) and to the inequality $\|F^T F - \mathbf{I}_3\| \geq \text{dist}(F, SO(3))$ if $\det(F) > 0$, we have

$$(6.4) \quad \widehat{W}(F) \geq \frac{c}{4} \text{dist}(F, SO(3))^2$$

for any matrix F .

Remark 6.1. As a classical example of a local elastic energy satisfying the above assumptions, we mention the following St Venant-Kirchhoff's law (see [6], [12]) for which

$$\widehat{W}(F) = \begin{cases} \frac{\lambda}{8} (\text{tr}(F^T F - \mathbf{I}_3))^2 + \frac{\mu}{4} \text{tr}((F^T F - \mathbf{I}_3)^2) & \text{if } \det(F) > 0 \\ +\infty & \text{if } \det(F) \leq 0. \end{cases}$$

In order to take into account the boundary condition on the admissible deformations we introduce the space

$$(6.5) \quad \mathbf{U}_\delta = \left\{ v \in (H^1(\mathcal{Q}_\delta))^3 \mid v = I_d \quad \text{on} \quad \Gamma_{0,\delta} \right\}.$$

Now we assume that the shell is submitted to applied volume forces $f_{\kappa,\delta} \in (L^2(\Omega_\delta))^3$ and we define the total energy $J_{\kappa,\delta}(v)$ over \mathbf{U}_δ by

$$(6.6) \quad J_{\kappa,\delta}(v) = \int_{\mathcal{Q}_\delta} \widehat{W}(\nabla_x v)(x) dx - \int_{\mathcal{Q}_\delta} f_{\kappa,\delta}(x) \cdot (v(x) - I_d(x)) dx.$$

To introduce the scaling on $f_{\kappa,\delta}$, let us consider f and g in $(L^2(\omega))^3$. Let $\kappa \geq 1$ and assume that the force $f_{\kappa,\delta}$ is given for $x = \Phi(s)$ by

$$(6.7) \quad f_{\kappa,\delta}(x) = \delta^{\kappa'} f(s_1, s_2) + \delta^{\kappa' - 2} s_3 g(s_1, s_2) \quad \text{for a.e. } x \in \mathcal{Q}_\delta.$$

where

$$(6.8) \quad \kappa' = \begin{cases} 2\kappa - 2 & \text{if } 1 \leq \kappa \leq 2, \\ \kappa & \text{if } \kappa \geq 2. \end{cases}$$

Using the rescaling Π_δ , the energy $J_{\kappa,\delta}$ can be alternatively written as

$$(6.9) \quad \begin{aligned} J_{\kappa,\delta}(v) = & \delta \int_{\Omega} W\left(\frac{1}{2}\Pi_\delta((\nabla_x v)^T \nabla_x v - \mathbf{I}_3)\right) \det\left(\mathbf{t}_1 + \delta S_3 \frac{\partial \mathbf{n}}{\partial s_1} | \mathbf{t}_2 + \delta S_3 \frac{\partial \mathbf{n}}{\partial s_2} | \mathbf{n}\right) ds_1 ds_2 dS_3 \\ & - \int_{\Omega} (\delta^{\kappa'+1} f + \delta^{\kappa'} S_3 g) \cdot \Pi_\delta(v - I_d) \det\left(\mathbf{t}_1 + \delta S_3 \frac{\partial \mathbf{n}}{\partial s_1} | \mathbf{t}_2 + \delta S_3 \frac{\partial \mathbf{n}}{\partial s_2} | \mathbf{n}\right) ds_1 ds_2 dS_3. \end{aligned}$$

We consider a deformation v of \mathbf{U}_δ such that

$$(6.10) \quad J_{\kappa,\delta}(v) \leq 0.$$

Notice that $J_{\kappa,\delta}(I_d) = 0$. Thanks to (2.4) and the two Korn's inequalities (3.6)-(3.7) and (6.7)-(6.8), we obtain the smallest following order for $\|\text{dist}(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}$ and $J_{\kappa,\delta}(v)$

$$(6.11) \quad \|\text{dist}(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)} \leq C\delta^{\kappa-1/2} \quad \text{and} \quad -c\delta^{2\kappa-1} \leq J_{\kappa,\delta}(v).$$

The constants do not depend on δ .

From the assumptions (6.3)-(6.4) on W , (6.7)-(6.8) on the applied forces and (6.10) on v , from the estimate (6.11) on $\|\text{dist}(\nabla_x v, SO(3))\|_{L^2(\mathcal{Q}_\delta)}$ and the Korn's inequalities (3.6)-(3.7) we deduce

$$\frac{c}{4} \|(\nabla_x v)^T \nabla_x v - \mathbf{I}_3\|_{(L^2(\mathcal{Q}_\delta))^{3 \times 3}}^2 \leq J_{\kappa,\delta}(v) + \int_{\mathcal{Q}_\delta} f_{\kappa,\delta} \cdot (v - I_d) \leq C\delta^{2\kappa-1}.$$

Hence, the following estimate of the Green-St Venant's tensor:

$$\left\| \frac{1}{2} \{(\nabla_x v)^T \nabla_x v - \mathbf{I}_3\} \right\|_{(L^2(\mathcal{Q}_\delta))^{3 \times 3}} \leq C\delta^{\kappa-1/2}.$$

We first obtain from the above inequality that $v \in (W^{1,4}(\mathcal{Q}_\delta))^3$ and moreover since $\kappa \geq 1$

$$\|\nabla_x v\|_{(L^4(\mathcal{Q}_\delta))^{3 \times 3}} \leq C\delta^{\frac{1}{4}}.$$

We set

$$m_{\kappa,\delta} = \inf_{v \in \mathbf{U}_\delta} J_{\kappa,\delta}(v).$$

As a consequence of (6.10) and the second inequality in (6.11) we have

$$-c \leq \frac{m_{\kappa,\delta}}{\delta^{2\kappa-1}} \leq 0.$$

We denote

$$(6.12) \quad m_\kappa = \liminf_{\delta \rightarrow 0} \frac{m_{\kappa,\delta}}{\delta^{2\kappa-1}}.$$

Remark 6.2. Let $v \in \mathbf{U}_\delta$ satisfyng (6.10). From the last estimate in (3.3) and (6.11), we have

$$\|\Pi_\delta(\nabla_x v - \mathbf{R})\|_{(L^2(\Omega))^{3 \times 3}}^2 \leq C\delta^{2\kappa-2}$$

and then we get that the set

$$\{s \in \Omega \mid \|\Pi_\delta(\nabla_x v - \mathbf{R})(s)\| \geq 1\}$$

has a measure less than $C\delta^{2\kappa-2}$. As a consequence when δ tends to 0, the set

$$\{s \in \Omega \mid \Pi_\delta[\det(\nabla_x v(s))] \leq 0\}$$

has a vanishing measure if $\kappa > 1$.

In general, a minimizer of $J_{\kappa,\delta}$ does not exist on \mathbf{U}_δ . In what follows, we replace the elastic functional $v \mapsto \frac{J_{\kappa,\delta}(v)}{\delta^{2\kappa-1}}$ on \mathbf{U}_δ by a simplified functional defined on \mathbb{D} which admits a minimum. Our aim, in this paper and forthcoming others, is to show that in (6.12) the lim of the lower bound for the elastic functional is in fact a limit and moreover this limit is equal to the limit of the minimum for the simplified functional. To do that, we will be brought to show that the asymptotic behavior of a minimizing sequence of deformations for the elastic functional is identical to that of a sequence of minimizer for the simplified functional. In Section 9, we prove this important result in the case $\kappa = 2$.

7. The simplified elastic model for shells

In this section we choose κ satisfying

$$\kappa > 1.$$

Let \mathbf{v} be in \mathbb{D}_{γ_0} and v the formal deformation associated to \mathbf{v} by (5.4). In order to introduce a simplified elastic energy and according to Section 5 and assumption 6.2, in a first step we replace the first term in (6.9) by $Q((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \widehat{E}_\delta(\mathbf{v})(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1})$. In a second step, we replace $\det(\mathbf{t}_1 + \delta S_3 \frac{\partial \mathbf{n}}{\partial s_1} | \mathbf{t}_2 + \delta S_3 \frac{\partial \mathbf{n}}{\partial s_2} | \mathbf{n})$ by $\det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})$. In a last step, Remark 6.2 leads us to omit the constraint $\det(\nabla v)$ in (6.3) in the simplified energy. Then if we set for all symmetric matrix F ,

$$(7.1) \quad W^s(F) = Q\left((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \widehat{F}(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}\right),$$

we replace the first term of (6.9) by $\delta \int_\Omega W^s(\widehat{E}_\delta(\mathbf{v})) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) ds_1 ds_2 dS_3$. In view of Proposition (5.1)

and in order to obtain the coerciveness of the simplified energy, the two terms $\delta^2 \left\| \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{t}_2 - \frac{\partial \mathbf{R}}{\partial s_2} \mathbf{t}_1 \right\|_{(L^2(\omega))^3}^2$, $\left\| \frac{\partial \mathcal{V}}{\partial s_1} \cdot \mathbf{R} \mathbf{t}_2 - \frac{\partial \mathcal{V}}{\partial s_2} \cdot \mathbf{R} \mathbf{t}_1 \right\|_{L^2(\omega)}^2$ are added to the simplified elastic one. As far as the term involving the forces in (6.9) are involved, we have using (5.4)

$$\begin{aligned} & \left| \int_\Omega (\delta^{\kappa'+1} f + \delta^{\kappa'} S_3 g) \cdot \Pi_\delta(v - I_d) \det(\mathbf{t}_1 + \delta S_3 \frac{\partial \mathbf{n}}{\partial s_1} | \mathbf{t}_2 + \delta S_3 \frac{\partial \mathbf{n}}{\partial s_2} | \mathbf{n}) ds_1 ds_2 dS_3 \right. \\ & \quad - 2\delta^{\kappa'+1} \int_\omega \left[f \cdot (\mathcal{V} - \phi) + \frac{1}{3} g \cdot (\mathbf{R} - \mathbf{I}_3) \mathbf{n} \right] \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) ds_1 ds_2 \\ & \quad \left. - \frac{2}{3} \delta^{\kappa'+1} \int_\omega g \cdot (\mathcal{V} - \phi) \left[\det\left(\frac{\partial \mathbf{n}}{\partial s_1} | \mathbf{t}_2 | \mathbf{n}\right) + \det\left(\mathbf{t}_1 | \frac{\partial \mathbf{n}}{\partial s_2} | \mathbf{n}\right) \right] ds_1 ds_2 \right| \\ & \leq C\delta^{\kappa'+2} (\|f\|_{(L^2(\omega))^3} + \|g\|_{(L^2(\omega))^3}) (\|\mathcal{V} - \phi\|_{(L^2(\omega))^3} + \|\mathbf{R} - \mathbf{I}_3\|_{(L^2(\omega))^{3 \times 3}} + \frac{1}{\delta^3} \|\bar{V}\|_{(L^2(\Omega))^3}). \end{aligned}$$

Then, in view of Proposition (5.1) and Corollary (5.2), we replace the terms with forces in (6.9) by

$$(7.2) \quad \begin{aligned} \mathcal{L}_{\kappa,\delta}(\mathcal{V}, \mathbf{R}) &= \delta^{\kappa'+1} \mathcal{L}(\mathcal{V}, \mathbf{R}), \\ \text{where } \mathcal{L}(\mathcal{V}, \mathbf{R}) &= 2 \int_{\omega} \left[f \cdot (\mathcal{V} - \phi) + \frac{1}{3} g \cdot (\mathbf{R} - \mathbf{I}_3) \mathbf{n} \right] \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) ds_1 ds_2 \\ &\quad + \frac{2}{3} \int_{\omega} g \cdot (\mathcal{V} - \phi) \left[\det \left(\frac{\partial \mathbf{n}}{\partial s_1} | \mathbf{t}_2 | \mathbf{n} \right) + \det \left(\mathbf{t}_1 | \frac{\partial \mathbf{n}}{\partial s_2} | \mathbf{n} \right) \right] ds_1 ds_2. \end{aligned}$$

The above considerations lead to the simplified total energy $J_{\kappa,\delta}^s(\cdot)$ defined by

$$(7.3) \quad \begin{cases} J_{\kappa,\delta}^s(\mathbf{v}) = \delta \left[\int_{\Omega} W^s(\widehat{E}_{\delta}(\mathbf{v})) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) ds_1 ds_2 dS_3 + \delta^2 \left\| \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{t}_2 - \frac{\partial \mathbf{R}}{\partial s_2} \mathbf{t}_1 \right\|_{(L^2(\omega))^3}^2 \right. \\ \left. + \left\| \frac{\partial \mathcal{V}}{\partial s_1} \cdot \mathbf{R} \mathbf{t}_2 - \frac{\partial \mathcal{V}}{\partial s_2} \cdot \mathbf{R} \mathbf{t}_1 \right\|_{L^2(\omega)}^2 \right] - \delta^{\kappa'+1} \mathcal{L}(\mathcal{V}, \mathbf{R}). \end{cases}$$

The end of this section is dedicated to show that the functional $J_{\kappa,\delta}^s$ admits a minimizer over \mathbb{D}_{γ_0} .

Let \mathbf{v} be in \mathbb{D}_{γ_0} we have

$$(7.4) \quad \left| \mathcal{L}(\mathcal{V}, \mathbf{R}) \right| \leq C (\|f\|_{(L^2(\omega))^3} + \|g\|_{(L^2(\omega))^3}) (\|\mathcal{V} - \phi\|_{(L^2(\omega))^3} + \|\mathbf{R} - \mathbf{I}_3\|_{(L^2(\omega))^{3 \times 3}}).$$

The quadratic form Q being positive, the definition (5.5) of $\mathcal{E}_{\delta}(\mathbf{v})$ and (7.3)-(7.4) give

$$C\delta \mathcal{E}_{\delta}(\mathbf{v}) - C\delta^{\kappa'+1} (\|f\|_{(L^2(\omega))^3} + \|g\|_{(L^2(\omega))^3}) (\|\mathcal{V} - \phi\|_{(L^2(\omega))^3} + \|\mathbf{R} - \mathbf{I}_3\|_{(L^2(\omega))^{3 \times 3}}) \leq J_{\kappa,\delta}^s(\mathbf{v}).$$

Now thanks to Corollary 5.2 and (6.8), we get, if $J_{\kappa,\delta}^s(\mathbf{v}) \leq 0 (= J_{\kappa,\delta}^s(\mathbf{I}_d))$

$$(7.5) \quad \mathcal{E}_{\delta}(\mathbf{v}) \leq C\delta^{2(\kappa-1)} (\|f\|_{(L^2(\omega))^3} + \|g\|_{(L^2(\omega))^3})^2.$$

Hence, there exists a constant c which does not depend on δ such that for any $\mathbf{v} \in \mathbb{D}_{\gamma_0}$ satisfying $J_{\kappa,\delta}^s(\mathbf{v}) \leq 0$, we have

$$c\delta^{2\kappa-1} \leq J_{\kappa,\delta}^s(\mathbf{v}).$$

We set

$$(7.6) \quad m_{\kappa,\delta}^s = \inf_{\mathbf{v} \in \mathbb{D}_{\gamma_0}} J_{\kappa,\delta}^s(\mathbf{v}).$$

As a consequence of the above inequality, we have

$$(7.7) \quad c \leq \frac{m_{\kappa,\delta}^s}{\delta^{2\kappa-1}} \leq 0.$$

In the following theorem we prove that for κ and δ fixed the minimization problem (7.6) has at least a solution.

Theorem 7.1. *There exists $\mathbf{v}_{\delta} \in \mathbb{D}_{\gamma_0}$ such that*

$$(7.8) \quad m_{\kappa,\delta}^s = J_{\kappa,\delta}^s(\mathbf{v}_{\delta}) = \min_{\mathbf{v} \in \mathbb{D}_{\gamma_0}} J_{\kappa,\delta}^s(\mathbf{v}).$$

Proof. Since $J_{\kappa,\delta}^s(\mathbf{I}_d) = 0$, we can consider a minimizing sequence \mathbf{v}_n in \mathbb{D}_{γ_0} such that $J_{\kappa,\delta}^s(\mathbf{v}_n) \leq 0$ and

$$m_{\kappa,\delta}^s = \lim_{n \rightarrow +\infty} J_{\kappa,\delta}^s(\mathbf{v}_n).$$

From (7.5) we get

$$\mathcal{E}_\delta(\mathbf{v}_n) \leq C\delta^{2(\kappa-1)}(\|f\|_{(L^2(\omega))^3} + \|g\|_{(L^2(\Omega))^3})^4.$$

Thanks to Corollary 5.2 and Proposition 5.1 the above estimate show that there exist a subsequence still denoted n such that (recall that $\|\mathbf{R}_n\|_{(L^\infty(\omega))^{3 \times 3}} = \sqrt{3}$)

$$(7.9) \quad \begin{cases} \mathcal{V}_n \rightharpoonup \mathcal{V} & \text{weakly in } (H^1(\omega))^3 \\ \mathbf{R}_n \rightharpoonup \mathbf{R} & \text{weakly in } (H^1(\omega))^{3 \times 3} \\ \mathbf{R}_n \rightarrow \mathbf{R} & \text{strongly in } (L^2(\omega))^{3 \times 3} \text{ and a.e. in } \omega \\ \bar{V}_n \rightharpoonup \bar{V} & \text{weakly in } (L^2(\omega; H^1(-1, 1)))^3. \end{cases}$$

Then setting $\mathbf{v} = (\mathcal{V}, \mathbf{R}, \bar{V}) \in \mathbb{D}_{\gamma_0}$, we get

$$\begin{aligned} \widehat{E}(\mathbf{v}_n) &\rightharpoonup \widehat{E}(\mathbf{v}) \quad \text{weakly in } (L^2(\Omega))^{3 \times 3}, \\ \frac{\partial \mathcal{V}_n}{\partial s_1} \cdot \mathbf{R}_n \mathbf{t}_2 - \frac{\partial \mathcal{V}_n}{\partial s_2} \cdot \mathbf{R}_n \mathbf{t}_1 &\rightharpoonup \frac{\partial \mathcal{V}}{\partial s_1} \cdot \mathbf{R} \mathbf{t}_2 - \frac{\partial \mathcal{V}}{\partial s_2} \cdot \mathbf{R} \mathbf{t}_1 \quad \text{weakly in } (L^2(\Omega))^3. \end{aligned}$$

Now, passing to the limit inf in $J_{\kappa,\delta}^s(\mathbf{v}_n)$, we obtain

$$m_{\kappa,\delta}^s \leq J_{\kappa,\delta}^s(\mathbf{v}) \leq \liminf_{n \rightarrow +\infty} J_{\kappa,\delta}^s(\mathbf{v}_n) = \lim_{n \rightarrow +\infty} J_{\kappa,\delta}^s(\mathbf{v}_n) = m_{\kappa,\delta}^s.$$

□

8. Asymptotic behavior of the simplified model. Case $\kappa = 2$.

In this section we study the asymptotic behavior of the sequence (\mathbf{v}_δ) of minimizer given in Theorem 7.1 and we characterize the limit of the minima $\frac{m_{2,\delta}^s}{\delta^3}$ as a minimum of a new functional. We denote \mathbb{D}_2 the following closed subset of \mathbb{D}_{γ_0} :

$$\mathbb{D}_2 = \left\{ \mathbf{v} \in \mathbb{D}_{\gamma_0} \mid \frac{\partial \mathcal{V}}{\partial s_\alpha} = \mathbf{R} \mathbf{t}_\alpha \right\}.$$

Notice that $\mathcal{V} \in (H^2(\omega))^3$. For all $\mathbf{v} = (\mathcal{V}, \mathbf{R}, \bar{V}) \in \mathbb{D}_2$, we have $(\mathcal{V}, \mathbf{R}, \delta^2 \bar{V}) \in \mathbb{D}_{\gamma_0}$ and

$$(8.1) \quad \frac{J_{2,\delta}^s(\mathcal{V}, \mathbf{R}, \delta^2 \bar{V})}{\delta^3} = \int_{\Omega} Q\left((\mathbf{t}_1 \mid \mathbf{t}_2 \mid \mathbf{n})^{-T} \widehat{\mathbf{E}}(\mathbf{v})(\mathbf{t}_1 \mid \mathbf{t}_2 \mid \mathbf{n})^{-1}\right) \det(\mathbf{t}_1 \mid \mathbf{t}_2 \mid \mathbf{n}) - \mathcal{L}(\mathcal{V}, \mathbf{R})$$

where

$$(8.2) \quad \widehat{E}(\mathbf{v}) = \begin{pmatrix} S_3 \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{n} \cdot \mathbf{R} \mathbf{t}_1 & S_3 \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{n} \cdot \mathbf{R} \mathbf{t}_2 & \frac{1}{2} \frac{\partial \bar{V}}{\partial S_3} \cdot \mathbf{t}_1 \\ * & S_3 \frac{\partial \mathbf{R}}{\partial s_2} \mathbf{n} \cdot \mathbf{R} \mathbf{t}_2 & \frac{1}{2} \frac{\partial \bar{V}}{\partial S_3} \cdot \mathbf{t}_2 \\ * & * & \frac{\partial \bar{V}}{\partial S_3} \cdot \mathbf{n} \end{pmatrix}$$

Notice that we have now $\frac{\partial \mathbf{R}}{\partial s_1} \mathbf{n} \cdot \mathbf{R} \mathbf{t}_2 = \frac{\partial \mathbf{R}}{\partial s_2} \mathbf{n} \cdot \mathbf{R} \mathbf{t}_1$. The right hand side of (8.1) does not depend on δ . We denote $\mathcal{J}_2(\mathbf{v})$ this right hand side

$$(8.3) \quad \mathcal{J}_2(\mathbf{v}) = \int_{\Omega} Q \left((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \widehat{\mathbf{E}}(\mathbf{v}) (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1} \right) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) - \mathcal{L}(\mathcal{V}, \mathbf{R}).$$

As in Theorem 7.1 we easily prove that there exists $\mathbf{v}_2 = (\mathcal{V}_2, \mathbf{R}_2, \bar{V}_2) \in \mathbb{D}_2$ such that

$$(8.4) \quad m_2^s = \mathcal{J}_2(\mathbf{v}_2) = \min_{\mathbf{v} \in \mathbb{D}_2} \mathcal{J}_2(\mathbf{v}).$$

Of course, due to (8.1) for all δ we have $\frac{m_{2,\delta}^s}{\delta^3} \leq m_2^s$. In the following theorem, we show that the limit of the left hand side of this inequality is equal to the right hand side.

Theorem 8.1. *We have*

$$m_2^s = \lim_{\delta \rightarrow 0} \frac{m_{2,\delta}^s}{\delta^3}.$$

Moreover, let $\mathbf{v}_\delta = (\mathcal{V}_\delta, \mathbf{R}_\delta, \bar{V}_\delta) \in \mathbb{D}_{\gamma_0}$ be a minimizer of the functional $J_{2,\delta}^s(\cdot)$, there exists a subsequence still denoted δ such that

$$(8.5) \quad \left\{ \begin{array}{l} \mathcal{V}_\delta \longrightarrow \mathcal{V}_0 \quad \text{strongly in } (H^1(\omega))^3, \\ \mathbf{R}_\delta \longrightarrow \mathbf{R}_0 \quad \text{strongly in } (H^1(\omega))^{3 \times 3}, \\ \frac{1}{\delta} \mathcal{Z}_{i\beta,\delta} \longrightarrow 0 \quad \text{strongly in } L^2(\omega), \\ \frac{1}{\delta^2} \bar{V}_\delta \longrightarrow \bar{V}_0 \quad \text{strongly in } (L^2(\omega; H^1(-1, 1)))^3. \end{array} \right.$$

We have

$$m_2^s = \mathcal{J}_2(\mathbf{v}_0).$$

Proof. We recall that we have

$$c \leq \frac{m_{2,\delta}^s}{\delta^3} = \frac{J_{2,\delta}^s(\mathbf{v}_\delta)}{\delta^3} = \min_{\mathbf{v} \in \mathbb{D}_{\gamma_0}} \frac{J_{2,\delta}^s(\mathbf{v})}{\delta^3}$$

and moreover with (7.5)

$$\mathcal{E}_\delta(\mathbf{v}_\delta) \leq C\delta^2 (\|f\|_{(L^2(\omega))^3} + \|g\|_{(L^2(\Omega))^3})^2.$$

Thanks to the estimates in Proposition 5.1, Corollary 5.2 and the above estimate we can extract a subsequence still denoted δ such that

$$(8.6) \quad \left\{ \begin{array}{l} \mathcal{V}_\delta \longrightarrow \mathcal{V}_0 \quad \text{strongly in } (H^1(\omega))^3, \\ \mathbf{R}_\delta \rightharpoonup \mathbf{R}_0 \quad \text{weakly in } (H^1(\omega))^{3 \times 3} \quad \text{and a.e. in } \omega, \\ \frac{1}{\delta^2} \bar{V}_\delta \rightharpoonup \bar{V}_0 \quad \text{weakly in } (L^2(\omega; H^1(-1, 1)))^3, \\ \frac{1}{\delta} \mathcal{Z}_{i\alpha,\delta} \rightharpoonup \mathcal{Z}_{i\alpha,0} \quad \text{weakly in } L^2(\omega), \\ \frac{1}{\delta} \left(\frac{\partial \mathcal{V}_\delta}{\partial s_\alpha} - \mathbf{R}_\delta \mathbf{t}_\alpha \right) \rightharpoonup Z_\alpha \quad \text{weakly in } (L^2(\omega))^3, \\ \left(\frac{\partial \mathbf{R}_\delta}{\partial s_1} \mathbf{t}_2 - \frac{\partial \mathbf{R}_\delta}{\partial s_2} \mathbf{t}_1 \right) \rightharpoonup Y \quad \text{weakly in } (L^2(\omega))^3, \\ \frac{1}{\delta} \left(\frac{\partial \mathcal{V}_\delta}{\partial s_1} \mathbf{R}_\delta \mathbf{t}_2 - \frac{\partial \mathcal{V}_\delta}{\partial s_2} \mathbf{R}_\delta \mathbf{t}_1 \right) \rightharpoonup X \quad \text{weakly in } (L^2(\omega))^3. \end{array} \right.$$

Then from the fifth convergence we obtain $\frac{\partial \mathcal{V}_0}{\partial s_\alpha} = \mathbf{R}_0 \mathbf{t}_\alpha$. So we have $\mathcal{V}_0 \in (H^2(\omega))^3$ and $\mathbf{v}_0 = (\mathcal{V}_0, \mathbf{R}_0, \bar{V}_0)$ belongs to \mathbb{D}_2 . From the above convergences, and upon extracting another subsequence, we also get

$$\frac{1}{\delta} \widehat{E}_\delta(\mathbf{v}_\delta) \rightharpoonup \mathbf{E}_0 = \begin{pmatrix} S_3 \frac{\partial \mathbf{R}_0}{\partial s_1} \mathbf{n} \cdot \mathbf{R}_0 \mathbf{t}_1 + \mathcal{Z}_{11,0} & S_3 \frac{\partial \mathbf{R}_0}{\partial s_1} \mathbf{n} \cdot \mathbf{R}_0 \mathbf{t}_2 + \mathcal{Z}_{12,0} & \frac{1}{2} \frac{\partial \bar{W}_0}{\partial S_3} \cdot \mathbf{t}_1 \\ * & S_3 \frac{\partial \mathbf{R}_0}{\partial s_2} \mathbf{n} \cdot \mathbf{R}_0 \mathbf{t}_2 + \mathcal{Z}_{22,0} & \frac{1}{2} \frac{\partial \bar{W}_0}{\partial S_3} \cdot \mathbf{t}_2 \\ * & * & \frac{\partial \bar{W}_0}{\partial S_3} \cdot \mathbf{n} \end{pmatrix} \text{ weakly in } (L^2(\Omega))^{3 \times 3}$$

where we have put

$$\bar{W}_0 = \bar{V}_0 + S_3 \mathcal{Z}_{31,0} \mathbf{t}'_1 + S_3 \mathcal{Z}_{32,0} \mathbf{t}'_2.$$

Passing to the limit we obtain

$$\begin{aligned} \int_{\Omega} Q\left((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \mathbf{E}_0 (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}\right) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) ds_1 ds_2 dS_3 + \|X\|_{(L^2(\omega))^3}^2 + \|Y\|_{(L^2(\omega))^3}^2 - \mathcal{L}(\mathcal{V}_0, \mathbf{R}_0) \\ \leq \liminf_{\delta \rightarrow 0} \frac{J_{2,\delta}^s(\mathbf{v}_\delta)}{\delta^3} = \lim_{\delta \rightarrow 0} \frac{m_{2,\delta}^s}{\delta^3}. \end{aligned}$$

In order to apply Lemma A in Appendix, we recall that if a function ψ belongs to $H^1(-1, 1)$ we have

$$\int_{-1}^1 \psi(S_3) S_3 dS_3 = 0 \iff \int_{-1}^1 \frac{d\psi}{dS_3}(S_3) (S_3^2 - 1) dS_3 = 0.$$

Then thanks to Lemma A we get

$$(8.7) \quad \min_{\mathbf{v} \in \mathbb{D}_2} \mathcal{J}_2(\mathbf{v}) \leq \int_{\Omega} Q\left((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \mathbf{E}_0 (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}\right) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) ds_1 ds_2 dS_3 - \mathcal{L}(\mathcal{V}_0, \mathbf{R}_0).$$

Hence $m_2^s \leq \liminf_{\delta \rightarrow 0} \frac{m_{2,\delta}^s}{\delta^3}$. Recall that we have $\frac{m_{2,\delta}^s}{\delta^3} \leq m_2^s$, so we have

$$\lim_{\delta \rightarrow 0} \frac{m_{2,\delta}^s}{\delta^3} = m_2^s.$$

Finally, from convergences (8.6) we obtain $\mathcal{Z}_{i\alpha,0} = 0$, $X = Y = 0$ and moreover we have the strong convergences in (8.5). \square

9. Justification of the simplified model. Case $\kappa = 2$

In this section, the introduction of the simplified energy is justified in the sense that we prove that both the minima of the elastic energy and of the simplified energy have the same limit as δ tends to 0.

Theorem 9.1. *We have*

$$m_2 = \lim_{\delta \rightarrow 0} \frac{m_{2,\delta}}{\delta^3} = \lim_{\delta \rightarrow 0} \frac{m_{2,\delta}^s}{\delta^3} = m_2^s.$$

Proof.

Step 1. In this step we prove that $m_2^s \leq m_2$. Let $(v_\delta)_{0 < \delta \leq \delta_0}$ be a minimizing sequence of deformations belonging to \mathbf{U}_δ and such that

$$(9.1) \quad m_2 = \lim_{\delta \rightarrow 0} \frac{J_{2,\delta}(v_\delta)}{\delta^3}.$$

From the estimates of Section 6 we get

$$(9.2) \quad \begin{cases} \|\text{dist}(\nabla_x v_\delta, SO(3))\|_{L^2(\mathcal{Q}_\delta)} \leq C\delta^{3/2}, \\ \left\| \frac{1}{2} \{ \nabla_x v_\delta^T \nabla_x v_\delta - \mathbf{I}_3 \} \right\|_{(L^2(\mathcal{Q}_\delta))^{3 \times 3}} \leq C\delta^{3/2}, \\ \|\nabla_x v_\delta\|_{(L^4(\mathcal{Q}_\delta))^{3 \times 3}} \leq C\delta^{1/4}. \end{cases}$$

We still denote by $\mathcal{V}_\delta(s_1, s_2) = \frac{1}{2\delta} \int_{-\delta}^{\delta} v_\delta(s_1, s_2, s_3) ds_3$ the mean of v_δ over the fibers of the shell. Upon extracting a subsequence (still indexed by δ), the results of [Note] and [JE] show that there exist $\mathcal{V} \in (H^2(\omega))^3$, $\mathbf{R} \in (H^1(\omega))^{3 \times 3}$ satisfying $\mathbf{R}(s_1, s_2)$ belongs to $SO(3)$ for a.e. $(s_1, s_2) \in \omega$, $\mathcal{Z}_{\alpha\beta} \in L^2(\omega)$ and $\overline{W} \in (L^2(\omega; H^1(-1, 1)))^3$ satisfying

$$(9.3) \quad \int_{-1}^1 \overline{W}(s_1, s_2, S_3) dS_3 = 0 \quad \text{for a.e. } (s_1, s_2) \in \omega, \quad \frac{\partial \mathcal{V}}{\partial s_\alpha} = \mathbf{R} \mathbf{t}_\alpha$$

together with the boundaries conditions $\mathcal{V} = \phi$, $\mathbf{R} = \mathbf{I}_3$ on γ_0 , and with the following convergences

$$(9.4) \quad \begin{cases} \Pi_\delta v_\delta \longrightarrow \mathcal{V} \text{ strongly in } (H^1(\Omega))^3, \\ \Pi_\delta(\nabla_x v_\delta) \longrightarrow \mathbf{R} \text{ strongly in } (L^2(\Omega))^{3 \times 3}, \\ \frac{\Pi_\delta(v_\delta - \mathcal{V}_\delta)}{\delta} \longrightarrow S_3(\mathbf{R} - \mathbf{I}_3)\mathbf{n} \text{ strongly in } (L^2(\Omega))^3, \\ \frac{1}{2\delta} \Pi_\delta((\nabla_x v_\delta)^T \nabla_x v_\delta - \mathbf{I}_3) \rightharpoonup (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \mathbf{E} (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1} \text{ weakly in } (L^2(\Omega))^9, \end{cases}$$

where

$$\mathbf{E} = \begin{pmatrix} S_3 \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{n} \cdot \mathbf{R} \mathbf{t}_1 + \mathcal{Z}_{11} & S_3 \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{n} \cdot \mathbf{R} \mathbf{t}_2 + \mathcal{Z}_{12} & \frac{1}{2} \frac{\partial \overline{W}}{\partial S_3} \cdot \mathbf{t}_1 \\ * & S_3 \frac{\partial \mathbf{R}}{\partial s_2} \mathbf{n} \cdot \mathbf{R} \mathbf{t}_2 + \mathcal{Z}_{22} & \frac{1}{2} \frac{\partial \overline{W}}{\partial S_3} \cdot \mathbf{t}_2 \\ * & * & \frac{\partial \overline{W}}{\partial S_3} \cdot \mathbf{n} \end{pmatrix}$$

Now, recall that

$$(9.5) \quad \frac{J_{2,\delta}(v_\delta)}{\delta^3} = \int_\Omega \frac{1}{\delta^2} W \left(\frac{1}{2} \Pi_\delta((\nabla_x v_\delta)^T \nabla_x v_\delta - \mathbf{I}_3) \right) \Pi_\delta \det(\nabla \Phi) - \frac{1}{\delta^3} \int_{\mathcal{Q}_\delta} f_{\kappa,\delta} \cdot (v_\delta - I_d).$$

In order to pass to the lim-inf in (9.5) we first notice that $\det(\nabla \Phi) = \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) + s_3 \det \left(\frac{\partial \mathbf{n}}{\partial s_1} | \mathbf{t}_2 | \mathbf{n} \right) + s_3 \det \left(\mathbf{t}_1 | \frac{\partial \mathbf{n}}{\partial s_2} | \mathbf{n} \right) + s_3^2 \det \left(\frac{\partial \mathbf{n}}{\partial s_1} | \frac{\partial \mathbf{n}}{\partial s_2} | \mathbf{n} \right)$ so that indeed $\Pi_\delta \det(\nabla \Phi)$ strongly converges to $\det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})$ in $L^\infty(\Omega)$ as δ tends to 0.

We now consider the first term of the right hand side. Let $\varepsilon > 0$ be fixed. Due to (6.2), there exists $\theta > 0$ such that

$$(9.6) \quad \forall E \in \mathbf{S}_3, \quad \|\|E\|\| \leq \theta, \quad W(E) \geq Q(E) - \varepsilon \|\|E\|\|^2.$$

We now use a similar argument given in [5]. Let us denote by χ_δ^θ the characteristic function of the set $A_\delta^\theta = \{s \in \Omega; \|\| \Pi_\delta((\nabla_x v_\delta)^T \nabla_x v_\delta - \mathbf{I}_3)(s) \|\| \geq \theta\}$. Due to (9.2), we have

$$(9.7) \quad \text{meas}(A_\delta^\theta) \leq C \frac{\delta^2}{\theta^2}.$$

Using the positive character of W , (9.2) and (9.6) give

$$\begin{aligned} \int_{\Omega} \frac{1}{\delta^2} \widehat{W}(\Pi_{\delta}(\nabla_x v_{\delta})) |\Pi_{\delta} \det(\nabla \Phi)| &\geq \int_{\Omega} \frac{1}{\delta^2} W\left(\frac{1}{2} \Pi_{\delta}((\nabla_x v_{\delta})^T \nabla_x v_{\delta} - \mathbf{I}_3)\right) (1 - \chi_{\delta}^{\theta}) \Pi_{\delta} \det(\nabla \Phi) \\ &\geq \int_{\Omega} Q\left(\frac{1}{2\delta} \Pi_{\delta}((\nabla_x v_{\delta})^T \nabla_x v_{\delta} - \mathbf{I}_3) (1 - \chi_{\delta}^{\theta})\right) \Pi_{\delta} \det(\nabla \Phi) - C\varepsilon \end{aligned}$$

In view of (9.7), the function χ_{δ}^{θ} converges a.e. to 0 as δ tends to 0 while the weak limit of $\frac{1}{2\delta} \Pi_{\delta}((\nabla_x v_{\delta})^T \nabla_x v_{\delta} - \mathbf{I}_3) (1 - \chi_{\delta}^{\theta})$ is given by (9.4). As a consequence and also using the convergence of $\Pi_{\delta} \det(\nabla \Phi)$ obtained above, we have

$$\liminf_{\delta \rightarrow 0} \int_{\Omega} \frac{1}{\delta^2} \widehat{W}(\Pi_{\delta}(\nabla_x v_{\delta})) \Pi_{\delta} \det(\nabla \Phi) \geq \int_{\Omega} Q\left((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \mathbf{E} (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}\right) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) - C\varepsilon.$$

As ε is arbitrary, this gives

$$(9.8) \quad \liminf_{\delta \rightarrow 0} \int_{\Omega} \frac{1}{\delta^2} \widehat{W}(\Pi_{\delta}(\nabla_x v_{\delta})) \Pi_{\delta} \det(\nabla \Phi) \geq \int_{\Omega} Q\left((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \mathbf{E} (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}\right) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}).$$

Using the convergences (9.4), it follows that

$$\lim_{\delta \rightarrow 0} \left(\frac{1}{\delta^3} \int_{\mathcal{Q}_{\delta}} f_{2,\delta} \cdot (v_{\delta} - I_d) \right) = \mathcal{L}(\mathcal{V}, \mathbf{R})$$

where $\mathcal{L}(\cdot, \cdot)$ is defined by (8.1). From (9.5), (9.8) and the above limit, we conclude that

$$(9.9) \quad m_2 = \lim_{\delta \rightarrow 0} \frac{J_{2,\delta}(v_{\delta})}{\delta^3} \geq \int_{\Omega} Q\left((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \mathbf{E} (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}\right) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) - \mathcal{L}(\mathcal{V}, \mathbf{R}).$$

Proceeding as in the proof of (8.7) in Section 8, we get

$$\int_{\Omega} Q\left((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \mathbf{E} (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}\right) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) - \mathcal{L}(\mathcal{V}, \mathbf{R}) \geq \min_{\mathbf{v} \in \mathbb{D}_2} \mathcal{J}_2(\mathbf{v}) = m_2^s.$$

Finally we have proved that $m_2^s \leq m_2$.

Step 2. In this step we prove that $m_2^s \geq m_2$.

Let us now consider a minimizer $\mathbf{v}_0 = (\mathcal{V}_0, \mathbf{R}_0, \bar{V}_0) \in \mathbb{D}_2$ of \mathcal{J}_2 and the sequence $\left((\mathcal{V}_{\delta}, \mathbf{R}_{\delta}, \bar{V}_{\delta})\right)_{\delta > 0}$ of approximation given by Lemma C of the Appendix. The deformation v_{δ} is now defined by

$$(9.10) \quad v_{\delta}(s) = \mathcal{V}_{\delta}(s_1, s_2) + \mathbf{R}_{\delta}(s_1, s_2) \left[s_3 \mathbf{n}(s_1, s_2) + \delta^2 \bar{V}_{\delta} \left(s_1, s_2, \frac{s_3}{\delta} \right) \right], \quad \text{for } s \in \Omega_{\delta}.$$

Step 2.1. Estimate on $\|\Pi_{\delta}(\nabla_x v_{\delta} - \mathbf{R}_{\delta})\|_{(L^{\infty}(\Omega))^3 \times 3}$ and $\|dist(\nabla_x v_{\delta}, SO(3))\|_{L^{\infty}(\omega)}$.

From (9.10) and through simple calculations, we first have

$$(9.11) \quad \begin{cases} (\nabla_x v_{\delta} - \mathbf{R}_{\delta}) \mathbf{t}_{\alpha} = \frac{\partial \mathcal{V}_{\delta}}{\partial s_{\alpha}} - \mathbf{R}_{\delta} \mathbf{t}_{\alpha} + s_3 \frac{\partial \mathbf{R}_{\delta}}{\partial s_{\alpha}} \mathbf{n} + \delta^2 \mathbf{R}_{\delta} \frac{\partial \bar{V}_{\delta}}{\partial s_{\alpha}} + \delta^2 \frac{\partial \mathbf{R}_{\delta}}{\partial s_{\alpha}} \bar{V}_{\delta} - (\nabla_x v_{\delta} - \mathbf{R}_{\delta}) s_3 \frac{\partial \mathbf{n}}{\partial s_{\alpha}} \\ (\nabla_x v_{\delta} - \mathbf{R}_{\delta}) \mathbf{n} = \delta \mathbf{R}_{\delta} \frac{\partial \bar{V}_{\delta}}{\partial s_3}, \end{cases}$$

then

$$(9.12) \quad \begin{aligned} & \Pi_\delta(\nabla_x v_\delta - \mathbf{R}_\delta) \cdot \Pi_\delta(\nabla_s \Phi) \\ &= \left(\frac{\partial \mathcal{V}_\delta}{\partial s_1} - \mathbf{R}_\delta \mathbf{t}_1 + S_3 \delta \frac{\partial \mathbf{R}_\delta}{\partial s_\alpha} \mathbf{n} + \delta^2 \frac{\partial(\mathbf{R}_\delta \bar{\mathbf{V}}_\delta)}{\partial s_\alpha} \mid \frac{\partial \mathcal{V}_\delta}{\partial s_2} - \mathbf{R}_\delta \mathbf{t}_2 + S_3 \delta \frac{\partial \mathbf{R}_\delta}{\partial s_\alpha} \mathbf{n} + \delta^2 \frac{\partial(\mathbf{R}_\delta \bar{\mathbf{V}}_\delta)}{\partial s_\alpha} \mid \delta \mathbf{R}_\delta \frac{\partial \bar{\mathbf{V}}_\delta}{\partial S_3} \right). \end{aligned}$$

Thanks to (2.3) and the estimates of Lemma C in Appendix we obtain

$$(9.13) \quad \|\Pi_\delta(\nabla_x v_\delta - \mathbf{R}_\delta)\|_{(L^\infty(\Omega))^{3 \times 3}} \leq \frac{1}{4}$$

and we deduce that there exists a positive constant C_0 such that

$$(9.14) \quad \|\Pi_\delta((\nabla_x v_\delta)^T \nabla_x v_\delta - \mathbf{I}_3)\|_{(L^\infty(\Omega))^{3 \times 3}} \leq C_0.$$

Again using the estimates in Lemma C we get

$$\|dist(\nabla_x v_\delta, SO(3))\|_{L^\infty(\omega)} \leq \frac{1}{2}$$

and then we obtain

$$(9.15) \quad \text{for a.e. } s \in \Omega_\delta \quad \det(\nabla_x v_\delta(s)) > 0.$$

Step 2.2. Strong limit of $\frac{1}{2\delta} \Pi_\delta((\nabla_x v_\delta)^T \nabla_x v_\delta - \mathbf{I}_3)$.

Thanks to the estimates and convergences of Lemma C and (9.12) we have

$$(9.16) \quad \|\Pi_\delta(\nabla_x v_\delta - \mathbf{R}_\delta)\|_{(L^2(\Omega))^{3 \times 3}} \leq C\delta.$$

We write the identity $(\nabla_x v_\delta)^T \nabla_x v_\delta - \mathbf{I}_3 = (\nabla_x v_\delta - \mathbf{R}_\delta)^T \mathbf{R}_\delta + \mathbf{R}_\delta^T (\nabla_x v_\delta - \mathbf{R}_\delta) + (\nabla_x v_\delta - \mathbf{R}_\delta)^T (\nabla_x v_\delta - \mathbf{R}_\delta) + (\mathbf{R}_\delta - \mathbf{R})^T \mathbf{R}_\delta + \mathbf{R}^T (\mathbf{R}_\delta - \mathbf{R})$. So, from (9.13) and (9.16) we get

$$(9.17) \quad \|\Pi_\delta((\nabla_x v_\delta)^T \nabla_x v_\delta - \mathbf{I}_3)\|_{(L^2(\Omega))^{3 \times 3}} \leq C\delta.$$

In view of (9.11), the strong convergences of Lemma C and (9.16) we deduce that

$$(9.18) \quad \begin{cases} \frac{1}{\delta} \Pi_\delta((\nabla_x v_\delta - \mathbf{R}) \mathbf{t}_\alpha) \longrightarrow S_3 \frac{\partial \mathbf{R}}{\partial s_\alpha} \mathbf{n} & \text{strongly in } (L^2(\Omega))^3 \\ \frac{1}{\delta} \Pi_\delta((\nabla_x v_\delta - \mathbf{R}) \mathbf{n}) \longrightarrow \mathbf{R} \frac{\partial \bar{\mathbf{V}}}{\partial S_3} \cdot \mathbf{n} & \text{strongly in } (L^2(\Omega))^3 \end{cases}$$

Now thanks (9.13) and the strong convergences (9.18) we obtain

$$\frac{1}{\sqrt{\delta}} \Pi_\delta(\nabla_x v_\delta - \mathbf{R}) \longrightarrow 0 \quad \text{strongly in } (L^4(\Omega))^3$$

and then using again Lemma C, (9.18) and the above decomposition of $(\nabla_x v_\delta)^T \nabla_x v_\delta - \mathbf{I}_3$, we get

$$(9.19) \quad \frac{1}{2\delta} \Pi_\delta((\nabla_x v_\delta)^T \nabla_x v_\delta - \mathbf{I}_3) \longrightarrow (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \widehat{\mathbf{E}}(\mathbf{v}_0) (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1} \quad \text{strongly in } (L^2(\Omega))^{3 \times 3},$$

where $\widehat{\mathbf{E}}(\mathbf{v}_0)$ is given by (8.2).

Step 2.3. Let ε be a fixed positive constant and let θ given by (7.1). We denote χ_δ^θ the characteristic function of the set $A_\delta^\theta = \{s \in \Omega; \|\Pi_\delta((\nabla_x v_\delta)^T \nabla_x v_\delta - \mathbf{I}_3)(s)\| \geq \theta\}$. Due to (9.17), we have

$$(9.20) \quad \text{meas}(A_\delta^\theta) \leq C \frac{\delta^2}{\theta^2}$$

and from (9.15) we have $\det(\nabla_x v_\delta(s)) > 0$ for a. e. $s \in \Omega_\delta$. Due to (6.2), (6.4) and (9.19) we deduce that

$$\begin{aligned} \overline{\lim}_{\delta \rightarrow 0} \int_\Omega \frac{1}{\delta^2} (1 - \chi_\delta^\theta) \widehat{W}(\Pi_\delta(\nabla_x v_\delta)) \Pi_\delta \det(\nabla \Phi) &\leq \int_\Omega Q\left((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \widehat{\mathbf{E}}(\mathbf{v}_0) (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}\right) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) \\ &+ \varepsilon \int_\Omega \left\| (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \widehat{\mathbf{E}}(\mathbf{v}_0) (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1} \right\|^2 \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) \end{aligned}$$

where $\widehat{\mathbf{E}}(\mathbf{v}_0)$ is given by (8.2). Thanks to (6.3), (6.4), (9.17), the continuity of W , the strong convergence (9.19) and the weak convergence $\frac{1}{\delta} \chi_\delta^\theta \rightarrow 0$ in $L^2(\Omega)$ we obtain

$$\lim_{\delta \rightarrow 0} \int_\Omega \frac{1}{\delta^2} \chi_\delta^\theta \widehat{W}(\Pi_\delta(\nabla_x v_\delta)) \Pi_\delta \det(\nabla \Phi) \leq C_1 \lim_{\delta \rightarrow 0} \int_\Omega \frac{1}{\delta} \chi_\delta^\theta \left\| \frac{1}{2\delta} \Pi_\delta((\nabla_x v_\delta)^T \nabla_x v_\delta - \mathbf{I}_3) \right\| \Pi_\delta \det(\nabla \Phi) = 0$$

Hence for any $\varepsilon > 0$ we get

$$\begin{aligned} \overline{\lim}_{\delta \rightarrow 0} \int_\Omega \frac{1}{\delta^2} \widehat{W}(\Pi_\delta(\nabla_x v_\delta)) \Pi_\delta \det(\nabla \Phi) &\leq \int_\Omega Q\left((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \widehat{\mathbf{E}}(\mathbf{v}_0) (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}\right) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) \\ &+ \varepsilon \int_\Omega \left\| (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \widehat{\mathbf{E}}(\mathbf{v}_0) (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1} \right\|^2 \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) \end{aligned}$$

Finally

$$(9.21) \quad \overline{\lim}_{\delta \rightarrow 0} \int_\Omega \frac{1}{\delta^2} \widehat{W}(\Pi_\delta(\nabla_x v_\delta)) \Pi_\delta \det(\nabla \Phi) \leq \int_\Omega Q\left((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \widehat{\mathbf{E}}(\mathbf{v}_0) (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}\right) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}).$$

As far as the contribution of the applied forces is concerned, we use the convergences of Lemma C to obtain

$$(9.22) \quad \lim_{\delta \rightarrow 0} \left(\frac{1}{\delta^3} \int_{Q_\delta} f_{2,\delta} \cdot (v_\delta - I_d) \right) = \mathcal{L}(\mathcal{V}, \mathbf{R}).$$

From (9.21) and (9.22), we conclude that

$$\overline{\lim}_{\delta \rightarrow 0} \frac{J_{2,\delta}(v_\delta)}{\delta^3} \leq \int_\Omega Q\left((\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \widehat{\mathbf{E}}(\mathbf{v}_0) (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}\right) \det(\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n}) - \mathcal{L}(\mathcal{V}, \mathbf{R}) = \mathcal{J}_2(\mathbf{v}_0) = m_2^s.$$

Then we get $m_2 \leq m_2^s$. □

10. Alternative formulations of the minima $m_{\kappa,\delta}^s$ and m_2 .

In the following theorem we characterize the minimum of the functional $J_{\kappa,\delta}^s(\cdot)$ over \mathbb{D}_{γ_0} , respectively \mathcal{J}_2 over \mathbb{D}_2 , as the minima of two functionals which depend on the mid-surface deformation \mathcal{V} and on the matrix \mathbf{R} which gives the rotation of the fibers.

The first theorem of this section shows that the variable \bar{w} can be eliminated in the minimization problem (7.8).

We set

$$\mathbb{E} = \left\{ (\mathcal{V}, \mathbf{R}) \in (H^1(\omega))^3 \times (H^1(\omega))^{3 \times 3} \mid \mathcal{V} = \phi, \quad \mathbf{R} = \mathbf{I}_3 \text{ on } \gamma_0, \right. \\ \left. \mathbf{R}(s_1, s_2) \in SO(3) \text{ for a.e. } (s_1, s_2) \in \omega \right\}.$$

We recall (see (5.3)) that for all $(\mathcal{V}, \mathbf{R}) \in \mathbb{E}$ we have set

$$\mathcal{Z}_{\alpha\beta} = \frac{1}{2} \left[\left(\frac{\partial \mathcal{V}}{\partial s_\alpha} - \mathbf{Rt}_\alpha \right) \cdot \mathbf{Rt}_\beta + \left(\frac{\partial \mathcal{V}}{\partial s_\beta} - \mathbf{Rt}_\beta \right) \cdot \mathbf{Rt}_\alpha \right], \quad \mathcal{Z}_{3\alpha} = \frac{\partial \mathcal{V}}{\partial s_\alpha} \cdot \mathbf{Rn} \\ \Gamma_{\alpha\beta}(\mathbf{R}) = \frac{1}{2} \left\{ \frac{\partial \mathbf{R}}{\partial s_\alpha} \mathbf{n} \cdot \mathbf{Rt}_\beta + \frac{\partial \mathbf{R}}{\partial s_\beta} \mathbf{n} \cdot \mathbf{Rt}_\alpha \right\}.$$

Theorem 10.1. *Let $\mathbf{v}_\delta = (\mathcal{V}_\delta, \mathbf{R}_\delta, \bar{V}_\delta) \in \mathbb{D}_{\gamma_0}$ be given by Theorem 7.1. The minimum $m_{\kappa, \delta}^s$ of the functional $\mathbf{v} \mapsto J_{\kappa, \delta}^s(\mathbf{v})$ over \mathbb{D}_{γ_0} satisfies the following minimization problem:*

$$(10.1) \quad m_{\kappa, \delta}^s = \mathcal{F}_{\kappa, \delta}^s(\mathcal{V}_\delta, \mathbf{R}_\delta) = \min_{(\mathcal{V}, \mathbf{R}) \in \mathbb{E}} \mathcal{F}_{\kappa, \delta}^s(\mathcal{V}, \mathbf{R})$$

where

$$(10.2) \quad \left\{ \begin{array}{l} \mathcal{F}_{\kappa, \delta}^s(\mathcal{V}, \mathbf{R}) = \delta^3 \int_{\omega} a_{\alpha\beta\alpha'\beta'} \Gamma_{\alpha\beta}(\mathbf{R}) \Gamma_{\alpha'\beta'}(\mathbf{R}) + \delta \int_{\omega} b_{i\alpha i' \alpha'} \mathcal{Z}_{i\alpha} \mathcal{Z}_{i' \alpha'} \\ + \delta^3 \left\| \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{t}_2 - \frac{\partial \mathbf{R}}{\partial s_2} \mathbf{t}_1 \right\|_{(L^2(\omega))^3}^2 + \delta \left\| \frac{\partial \mathcal{V}}{\partial s_1} \cdot \mathbf{Rt}_2 - \frac{\partial \mathcal{V}}{\partial s_2} \cdot \mathbf{Rt}_1 \right\|_{L^2(\omega)}^2 - \delta^{\kappa'+1} \mathcal{L}(\mathcal{V}, \mathbf{R}). \end{array} \right.$$

The $a_{\alpha\beta\alpha'\beta'}$ and $b_{i\alpha i' \alpha'}$ are constants which depend only of the quadratic form Q and the vectors $(\mathbf{t}_1, \mathbf{t}_2, \mathbf{n})$.

Proof. In order to eliminate \bar{V} , we fix $(\mathcal{V}, \mathbf{R}) \in \mathbb{E}$ and we minimize the functional $J_{\kappa, \delta}^s(\mathbf{v})$ over the space $(\alpha = 1, 2)$

$$\mathbf{V} = \left\{ \bar{V} \in (L^2(\omega; H^1(-1, 1)))^3 \mid \int_{-1}^1 \bar{V}_i(s_1, s_2, S_3) dS_3 = \int_{-1}^1 S_3 \bar{V}(s_1, s_2, S_3) \mathbf{t}_\alpha dS_3 = 0, \text{ for a.e. } (s_1, s_2) \in \omega \right\}.$$

We apply Lemma B in Appendix with

$$\mathbf{a} = \begin{pmatrix} \Gamma_{11}(\mathbf{R}) \\ \Gamma_{12}(\mathbf{R}) \\ \Gamma_{22}(\mathbf{R}) \end{pmatrix}, \quad \mathbf{b} = \frac{1}{\delta} \begin{pmatrix} \mathcal{Z}_{11} \\ \mathcal{Z}_{12} \\ \mathcal{Z}_{22} \end{pmatrix}, \quad \mathbf{d} = \frac{1}{\delta} \begin{pmatrix} \mathcal{Z}_{31} \\ \mathcal{Z}_{32} \\ 0 \end{pmatrix}.$$

We obtain immediately the theorem. □

The next theorem is similar to Theorem 10.1 for the limit energy and the minimization problem (8.4).

We set

$$\mathbb{E}_{lim} = \left\{ (\mathcal{V}, \mathbf{R}) \in \mathbb{E} \mid \frac{\partial \mathcal{V}}{\partial s_\alpha} = \mathbf{Rt}_\alpha, \quad \alpha = 1, 2 \right\}.$$

Theorem 10.2. *Let $(\mathcal{V}_0, \mathbf{R}_0)$ be given by Theorem 9.2. The minimum m_2 of the functional \mathcal{J}_2 over \mathbf{D}_2 satisfies the following minimization problem:*

$$(10.3) \quad m_2 = \mathcal{F}_2(\mathcal{V}_0, \mathbf{R}_0) = \min_{(\mathcal{V}, \mathbf{R}) \in \mathbb{E}_{lim}} \mathcal{F}_2(\mathcal{V}, \mathbf{R})$$

where

$$(10.4) \quad \mathcal{F}_2(\mathcal{V}, \mathbf{R}) = \int_{\omega} a_{\alpha\beta\alpha'\beta'} \left(\frac{\partial \mathbf{R}}{\partial s_\alpha} \mathbf{n} \cdot \mathbf{Rt}_\beta \right) \left(\frac{\partial \mathbf{R}}{\partial s_{\alpha'}} \mathbf{n} \cdot \mathbf{Rt}_{\beta'} \right) - \mathcal{L}(\mathcal{V}, \mathbf{R})$$

The $a_{\alpha\beta\alpha'\beta'}$ are the same constants as the one in Theorem 10.1.

Proof. We proceed as in Theorem 10.1. In order to eliminate \bar{V} , we fix $(\mathcal{V}, \mathbf{R}) \in \mathbb{E}_{lim}$ and we minimize the functional $\mathcal{J}_2(\mathcal{V}, \mathbf{R}, \cdot)$ over the space \mathbf{V} . Thanks to Lemmas A and B in Appendix we obtain the minimum with respect to \bar{V} and then the new characterization of the minimum m_2 . \square

Of course, for all $(\mathcal{V}, \mathbf{R}) \in \mathbb{E}_{lim}$, we get

$$\mathcal{F}_{2,\delta}^s(\mathcal{V}, \mathbf{R}) = \delta^3 \mathcal{F}_2(\mathcal{V}, \mathbf{R}).$$

Let us give the explicit expression of the limit energies $\mathcal{F}_{\kappa,\delta}^s$ and \mathcal{F}_2 in the case where S is a developable surface such that the parametrization ϕ is locally isometric

$$\forall (s_1, s_2) \in \bar{\omega} \quad \|\mathbf{t}_\alpha(s_1, s_2)\|_2 = 1 \quad \mathbf{t}_1(s_1, s_2) \cdot \mathbf{t}_2(s_1, s_2) = 0.$$

We consider a St Venant-Kirchhoff's law for which we have

$$\widehat{W}(F) = \begin{cases} \frac{\lambda}{8} (tr(F^T F - \mathbf{I}_3))^2 + \frac{\mu}{4} tr((F^T F - \mathbf{I}_3)^2) & \text{if } \det(F) > 0 \\ +\infty & \text{if } \det(F) \leq 0, \end{cases}$$

so that $Q = W = W^s$.

Expression of $\mathcal{F}_{\kappa,\delta}^s$. For any $\mathbf{v} = (\mathcal{V}, \mathbf{R}, \bar{V}) \in \mathbb{D}_{\gamma_0}$, the expression (7.3) gives

$$(10.5) \quad \begin{cases} \mathcal{J}_{\kappa,\delta}^s(\mathbf{v}) = \delta \int_{\Omega} \left[\frac{\lambda}{2} (tr(\widehat{E}_\delta(\mathbf{v})))^2 + \mu tr((\widehat{E}_\delta(\mathbf{v}))^2) \right] + \delta^3 \left\| \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{t}_2 - \frac{\partial \mathbf{R}}{\partial s_2} \mathbf{t}_1 \right\|_{(L^2(\omega))^3}^2 \\ + \delta \left\| \frac{\partial \mathcal{V}}{\partial s_1} \cdot \mathbf{R} \mathbf{t}_2 - \frac{\partial \mathcal{V}}{\partial s_2} \cdot \mathbf{R} \mathbf{t}_1 \right\|_{L^2(\omega)}^2 - \delta^{\kappa'+1} \mathcal{L}(\mathcal{V}, \mathbf{R}). \end{cases}$$

where $\widehat{E}_\delta(\mathbf{v})$ is defined by (5.3). It follows that the elimination of \bar{V} in Theorem 10.1 gives the partial derivatives of \bar{V} with respect to S_3

$$(10.6) \quad \begin{pmatrix} \frac{\partial \bar{V}}{\partial S_3}(\cdot, \cdot, S_3) \cdot \mathbf{R} \mathbf{t}_1 \\ \frac{\partial \bar{V}}{\partial S_3}(\cdot, \cdot, S_3) \cdot \mathbf{R} \mathbf{t}_2 \\ \frac{\partial \bar{V}}{\partial S_3}(\cdot, \cdot, S_3) \cdot \mathbf{R} \mathbf{n} \end{pmatrix} = \delta \begin{pmatrix} -\mathcal{Z}_{31} \left(1 + \frac{5}{4} (S_3^2 - 1) \right) \\ -\mathcal{Z}_{32} \left(1 + \frac{5}{4} (S_3^2 - 1) \right) \\ -\frac{\nu}{1-\nu} \left(\delta S_3 [\Gamma_{11}(\mathbf{R}) + \Gamma_{22}(\mathbf{R})] + [\mathcal{Z}_{11} + \mathcal{Z}_{22}] \right) \end{pmatrix}$$

and then

$$\begin{aligned} \mathcal{F}_{\kappa,\delta}^s(\mathcal{V}, \mathbf{R}) &= \frac{E\delta^3}{3(1-\nu^2)} \int_{\omega} \left[(1-\nu) \sum_{\alpha,\beta=1}^2 (\Gamma_{\alpha\beta}(\mathbf{R}))^2 + \nu (\Gamma_{11}(\mathbf{R}) + \Gamma_{22}(\mathbf{R}))^2 \right] \\ &+ \frac{E\delta}{(1-\nu^2)} \int_{\omega} \left[(1-\nu) \sum_{\alpha,\beta=1}^2 (\mathcal{Z}_{\alpha\beta})^2 + \nu (\mathcal{Z}_{11} + \mathcal{Z}_{22})^2 \right] + \frac{5E\delta}{12(1+\nu)} \int_{\omega} (\mathcal{Z}_{31}^2 + \mathcal{Z}_{32}^2) \\ &+ \delta^3 \left\| \frac{\partial \mathbf{R}}{\partial s_1} \mathbf{t}_2 - \frac{\partial \mathbf{R}}{\partial s_2} \mathbf{t}_1 \right\|_{(L^2(\omega))^3}^2 + \delta \left\| \frac{\partial \mathcal{V}}{\partial s_1} \cdot \mathbf{R} \mathbf{t}_2 - \frac{\partial \mathcal{V}}{\partial s_2} \cdot \mathbf{R} \mathbf{t}_1 \right\|_{L^2(\omega)}^2 - \delta^{\kappa'+1} \mathcal{L}(\mathcal{V}, \mathbf{R}). \end{aligned}$$

Expression of \mathcal{F}_2 . For any $\mathbf{v} = (\mathcal{V}, \mathbf{R}, \bar{V}) \in \mathbb{D}_2$, the expression (8.3) gives

$$\mathcal{J}_2(\mathbf{v}) = \int_{\Omega} \left[\frac{\lambda}{2} (tr(\widehat{\mathbf{E}}(\mathbf{v})))^2 + \mu tr((\widehat{\mathbf{E}}(\mathbf{v}))^2) \right] - \mathcal{L}(\mathcal{V}, \mathbf{R})$$

where $\widehat{\mathbf{E}}(\mathbf{v})$ is defined by (8.2). It follows that the elimination of \bar{V} in Theorem 10.2 is identical to that of standard linear elasticity (see [19]) hence we have

$$(10.7) \quad \bar{V}(\cdot, \cdot, S_3) = -\frac{\nu}{2(1-\nu)} \left(S_3^2 - \frac{1}{3} \right) \left[\Gamma_{11}(\mathbf{R}) + \Gamma_{22}(\mathbf{R}) \right]$$

and then

$$\mathcal{F}_2(\mathcal{V}, \mathbf{R}) = \frac{E}{3(1-\nu^2)} \int_{\omega} \left[(1-\nu) \sum_{\alpha, \beta=1}^2 (\Gamma_{\alpha\beta}(\mathbf{R}))^2 + \nu (\Gamma_{11}(\mathbf{R}) + \Gamma_{22}(\mathbf{R}))^2 \right] - \mathcal{L}(\mathcal{V}, \mathbf{R}).$$

Remark 10.1. In the case of a St-Venant-Kirchhoff material a classical energy argument show that if $(v_\delta)_{0 < \delta \leq \delta_0}$ is a sequence such that

$$m_2 = \lim_{\delta \rightarrow 0} \frac{J_{2,\delta}(v_\delta)}{\delta^3},$$

then there exists a subsequence and $(\mathcal{V}_0, \mathbf{R}_0) \in \mathbb{E}$, which is a solution of Problem (10.3), such that the sequence of the Green-St Venant's deformation tensors satisfies

$$\frac{1}{2\delta} \Pi_\delta((\nabla_x v_\delta)^T \nabla_x v_\delta - \mathbf{I}_3) \longrightarrow (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \widehat{\mathbf{E}}(\mathbf{v}_0) (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-T} \quad \text{strongly in } (L^2(\Omega))^{3 \times 3},$$

where $\widehat{\mathbf{E}}(\mathbf{v}_0)$ is defined in (8.2) with \bar{V}_0 given by (10.7) (replacing \mathbf{R} by \mathbf{R}_0).

Remark 10.2. It is well known that the constraint $\frac{\partial \mathcal{V}}{\partial s_1} = \mathbf{Rt}_1$ and $\frac{\partial \mathcal{V}}{\partial s_2} = \mathbf{Rt}_2$ together the boundary conditions are strong limitations on the possible deformation for the limit 2d shell. Actually for a plate or as soon as S is a developable surface, the configuration after deformation must also be a developable surface. In the general case, it is an open problem to know if the set \mathbb{E}_{lim} contains other deformations than identity mapping or very special isometries (as for example symetries).

Appendix.

Lemma A. Let \mathcal{Q}_m be the positive definite quadratic form defined on the space $\mathbb{R}^3 \times \mathbb{R}^3 \times (L^2(-1, 1))^3$ by

$$\forall (\mathbf{a}, \mathbf{b}, \mathbf{c}) \in \mathbb{R}^3 \times \mathbb{R}^3 \times (L^2(-1, 1))^3, \quad \mathcal{Q}_m(\mathbf{a}, \mathbf{b}, \mathbf{c}) = \int_{-1}^1 \mathbf{A}(S_3) \begin{pmatrix} S_3 \mathbf{a}_1 + \mathbf{b}_1 \\ S_3 \mathbf{a}_2 + \mathbf{b}_2 \\ S_3 \mathbf{a}_3 + \mathbf{b}_3 \\ \mathbf{c}_1(S_3) \\ \mathbf{c}_2(S_3) \\ \mathbf{c}_3(S_3) \end{pmatrix} \cdot \begin{pmatrix} S_3 \mathbf{a}_1 + \mathbf{b}_1 \\ S_3 \mathbf{a}_2 + \mathbf{b}_2 \\ S_3 \mathbf{a}_3 + \mathbf{b}_3 \\ \mathbf{c}_1(S_3) \\ \mathbf{c}_2(S_3) \\ \mathbf{c}_3(S_3) \end{pmatrix} dS_3$$

where $\mathbf{A}(S_3)$ is a symmetric positive definite 6×6 matrix satisfying

$$(A.1) \quad \mathbf{A}(S_3) = \mathbf{A}(-S_3) \quad \text{for a.e. } S_3 \in]-1, 1[$$

and moreover there exists a positive constant c such that

$$(A.2) \quad \forall \xi \in \mathbb{R}^6, \quad \mathbf{A}(S_3) \xi \cdot \xi \geq c |\xi|^2 \quad \text{for a.e. } S_3 \in]-1, 1[.$$

For all $\mathbf{a} \in \mathbb{R}^3$, we have

$$\min_{(\mathbf{b}, \mathbf{c}) \in \mathbb{R}^3 \times (L^2(-1, 1))^3} \mathcal{Q}_m(\mathbf{a}, \mathbf{b}, \mathbf{c}) = \min_{\mathbf{c} \in \mathbf{L}_2} \mathcal{Q}_m(\mathbf{a}, 0, \mathbf{c})$$

where

$$\mathbf{L}_2 = \left\{ \mathbf{c} \in (L^2(-1, 1))^3 \mid \int_{-1}^1 \mathbf{c}_\alpha(S_3)(S_3^2 - 1)dS_3 = 0, \alpha \in \{1, 2\} \right\}.$$

Proof. We write

$$\mathbf{A}(S_3) = \begin{pmatrix} \mathbf{A}_1(S_3) & \vdots & \mathbf{A}_2(S_3) \\ \dots & & \dots \\ \mathbf{A}_2^T(S_3) & \vdots & \mathbf{A}_3(S_3) \end{pmatrix}$$

where for a.e. $S_3 \in]-1, 1[$, $\mathbf{A}_1(S_3)$ and $\mathbf{A}_3(S_3)$ are symmetric positive definite 3×3 matrices. The both minimum are obtained with

$$\mathbf{c}_0(S_3) = -\mathbf{A}_3^{-1}(S_3)\mathbf{A}_2^T(S_3)S_3\mathbf{a}, \quad \mathbf{b}_0 = 0.$$

We have

$$(A.3) \quad \mathcal{Q}_m(\mathbf{a}, 0, \mathbf{c}_0) = \left(\int_{-1}^1 S_3^2 (\mathbf{A}_1(S_3) - \mathbf{A}_2(S_3)\mathbf{A}_3^{-1}(S_3)\mathbf{A}_2^T(S_3))dS_3 \right) \mathbf{a} \cdot \mathbf{a}.$$

□

In the following lemma we use the same notation as in Lemma A.

Lemma B. *Let \mathbf{a}, \mathbf{b} be two fixed vectors in \mathbb{R}^3 and let \mathbf{d} be a fixed vector in $\mathbb{R}^2 \times \{0\}$. We have*

$$(B.1) \quad \min_{\mathbf{c} \in \mathbf{L}_2} \mathcal{Q}_m(\mathbf{a}, \mathbf{b}, \mathbf{c} + \mathbf{d}) = \left(\int_{-1}^1 S_3^2 [\mathbf{A}_1(S_3) - \mathbf{A}_2(S_3)\mathbf{A}_3^{-1}(S_3)\mathbf{A}_2^T(S_3)] \right) \mathbf{a} \cdot \mathbf{a} + Q'_m(\mathbf{b}, \mathbf{d})$$

where Q'_m is a positive definite quadratic form which depends only on the matrix \mathbf{A} .

Proof. Through solving a simple variational problem, we find that the minimum of the functional $\mathbf{c} \mapsto \mathcal{Q}_m(\mathbf{a}, \mathbf{b}, \mathbf{c} + \mathbf{d})$ over the space \mathbf{L}_2 is obtained with

$$\mathbf{c}(S_3) = -\mathbf{d} - \mathbf{A}_3^{-1}(S_3)\mathbf{A}_2^T(S_3)(S_3\mathbf{a} + \mathbf{b}) + (S_3^2 - 1)\mathbf{A}_3^{-1}(S_3)\mathbf{e}$$

where $\mathbf{e} \in \mathbb{R}^2 \times \{0\}$

$$\mathbf{e} = e_1\mathbf{e}_1 + e_2\mathbf{e}_2, \quad \mathbf{e}_1 = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad \mathbf{e}_2 = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

is the solution of the system

$$\left[\frac{4}{3}\mathbf{d} - \left(\int_{-1}^1 (S_3^2 - 1)\mathbf{A}_3^{-1}(S_3)\mathbf{A}_2^T(S_3)dS_3 \right) \mathbf{b} + \left(\int_{-1}^1 (S_3^2 - 1)^2\mathbf{A}_3^{-1}(S_3)dS_3 \right) \mathbf{e} \right] \cdot \mathbf{e}_\alpha = 0, \quad \alpha = 1, 2.$$

Notice that the matrix $\int_{-1}^1 (S_3^2 - 1)^2\mathbf{A}_3^{-1}(S_3)dS_3$ is a 3×3 symmetric positive definite matrix. Replacing \mathbf{c} and \mathbf{e} by their values we obtain (B.1). □

Lemma C. *Let $(\mathcal{V}, \mathbf{R}, \bar{\mathcal{V}})$ be in \mathbf{D}_2 , there exists a sequence $\left((\mathcal{V}_\delta, \mathbf{R}_\delta, \bar{\mathcal{V}}_\delta) \right)_{\delta > 0}$ of $(W^{2,\infty}(\omega))^3 \times (W^{1,\infty}(\omega))^{3 \times 3} \times (W^{1,\infty}(\Omega))^3$ such that*

$$(C.1) \quad \mathcal{V}_\delta = \phi, \quad \mathbf{R}_\delta = \mathbf{I}_3 \quad \text{on } \gamma_0, \quad \bar{\mathcal{V}}_\delta = 0, \quad \text{on } \gamma_0 \times]-1, 1[$$

with

$$(C.2) \quad \left\{ \begin{array}{l} \mathcal{V}_\delta \longrightarrow \mathcal{V} \quad \text{strongly in} \quad (H^2(\omega))^3 \\ \mathbf{R}_\delta \longrightarrow \mathbf{R} \quad \text{strongly in} \quad (H^1(\omega))^{3 \times 3} \\ \frac{1}{\delta}(\mathbf{R}_\delta - \mathbf{R}) \longrightarrow 0 \quad \text{strongly in} \quad (L^2(\omega))^{3 \times 3} \\ \frac{1}{\delta} \left(\frac{\partial \mathcal{V}_\delta}{\partial s_\alpha} - \mathbf{R}_\delta \mathbf{t}_\alpha \right) \longrightarrow 0 \quad \text{strongly in} \quad (L^2(\omega))^3 \\ \bar{\mathcal{V}}_\delta \longrightarrow \bar{\mathcal{V}} \quad \text{strongly in} \quad (L^2(\omega; H^1((-1, 1)))^3, \\ \delta \frac{\partial \bar{\mathcal{V}}_\delta}{\partial s_\alpha} \longrightarrow 0 \quad \text{strongly in} \quad (L^2(\Omega))^3, \end{array} \right.$$

and moreover

$$(C.3) \quad \left\{ \begin{array}{l} \| \text{dist}(\mathbf{R}_\delta, SO(3)) \|_{L^\infty(\omega)} \leq \frac{1}{8}, \quad \left\| \frac{\partial \mathcal{V}_\delta}{\partial s_\alpha} - \mathbf{R}_\delta \mathbf{t}_\alpha \right\|_{(L^\infty(\omega))^3} \leq \frac{1}{8}, \\ \| \mathbf{R}_\delta \|_{(W^{1,\infty}(\omega))^{3 \times 3}}^2 + \| \mathbf{R}_\delta \bar{\mathcal{V}}_\delta \|_{(W^{1,\infty}(\Omega))^3}^2 \leq \frac{1}{(4c'_1 \delta)^2}. \end{array} \right.$$

The constant c'_1 is given by (2.3).

Proof. For $h > 0$ small enough, consider a $C_0^\infty(\mathbb{R}^2)$ -function ψ_h such that $0 \leq \psi_h \leq 1$

$$\begin{cases} \psi_h(s_1, s_2) = 1 & \text{if } \text{dist}((s_1, s_2), \gamma_0) \leq h \\ \psi_h(s_1, s_2) = 0 & \text{if } \text{dist}((s_1, s_2), \gamma_0) \geq 2h. \end{cases}$$

Indeed we can assume that

$$(C.4) \quad \| \psi_h \|_{W^{1,\infty}(\mathbb{R}^2)} \leq \frac{C}{h}, \quad \| \psi_h \|_{W^{2,\infty}(\mathbb{R}^2)} \leq \frac{C}{h^2}.$$

Since ω is bounded with a Lipschitz boundary, we first extend the fields \mathcal{V} and $\mathbf{R}_\mathbf{n} = \mathbf{R}\mathbf{n}$ into two fields of $(H^2(\mathbb{R}^2))^3$ and $(H^1(\mathbb{R}^2))^3$ (and we use the same notations for these extensions). We define the 3×3 matrix field $\mathbf{R}' \in (H^1(\mathbb{R}^2))^{3 \times 3}$ by the formula

$$(C.5) \quad \mathbf{R}' = \left(\frac{\partial \mathcal{V}}{\partial s_1} \Big|_{\frac{\partial \mathcal{V}}{\partial s_2}} \Big|_{\mathbf{R}_\mathbf{n}} \right) (\mathbf{t}_1 | \mathbf{t}_2 | \mathbf{n})^{-1}.$$

By construction we have $\frac{\partial \mathcal{V}}{\partial s_\alpha} = \mathbf{R}' \mathbf{t}_\alpha$ in \mathbb{R}^2 and $\mathbf{R}' = \mathbf{R}$ in ω . At least, we introduce below the approximations \mathcal{V}_h and \mathbf{R}_h of \mathcal{V} and \mathbf{R} as restrictions to $\bar{\omega}$ of the following fields defined into \mathbb{R}^2 :

$$(C.6) \quad \begin{cases} \mathcal{V}'_h(s_1, s_2) = \frac{1}{9\pi h^2} \int_{B(0,3h)} \mathcal{V}(s_1 + t_1, s_2 + t_2) dt_1 dt_2, \\ \mathbf{R}'_h(s_1, s_2) = \frac{1}{9\pi h^2} \int_{B(0,3h)} \mathbf{R}'(s_1 + t_1, s_2 + t_2) dt_1 dt_2, \end{cases} \quad \text{a.e. } (s_1, s_2) \in \mathbb{R}^2$$

and

$$(C.7) \quad \mathcal{V}_h = \phi \psi_h + \mathcal{V}'_h(1 - \psi_h), \quad \mathbf{R}_h = \mathbf{I}_3 \psi_h + \mathbf{R}'_h(1 - \psi_h), \quad \text{in } \omega.$$

Notice that we have

$$(C.8) \quad \begin{aligned} \mathcal{V}'_h &\in (W^{2,\infty}(\mathbb{R}^2))^3, & \mathbf{R}'_h &\in (W^{1,\infty}(\mathbb{R}^2))^{3\times 3}, \\ \mathcal{V}_h &\in (W^{2,\infty}(\omega))^3, & \mathbf{R}_h &\in (W^{1,\infty}(\omega))^{3\times 3}, & \mathcal{V}_h = \phi, & \mathbf{R}_h = \mathbf{I}_3 \text{ on } \gamma_0. \end{aligned}$$

Due to the definition (C.5) of \mathbf{R}' and in view of (C.6) we have

$$(C.9) \quad \begin{cases} \mathcal{V}'_h \longrightarrow \mathcal{V} & \text{strongly in } (H^2(\mathbb{R}^2))^3, \\ \mathbf{R}'_h \longrightarrow \mathbf{R}' & \text{strongly in } (H^1(\mathbb{R}^2))^{3\times 3} \end{cases}$$

and thus using estimates (C.4)

$$(C.10) \quad \begin{cases} \mathcal{V}_h \longrightarrow \mathcal{V} & \text{strongly in } (H^2(\omega))^3, \\ \mathbf{R}_h \longrightarrow \mathbf{R} & \text{strongly in } (H^1(\omega))^{3\times 3} \end{cases}$$

Moreover using again (C.6) and the fact that $\mathbf{R}' - \mathbf{R}_h$ strongly converges to 0 in $(H^1(\mathbb{R}^2))^{3\times 3}$ we deduce that

$$\frac{1}{h}(\mathbf{R}'_h - \mathbf{R}') \longrightarrow 0 \quad \text{strongly in } (L^2(\mathbb{R}^2))^{3\times 3}$$

and then together with (C.4), (C.5), (C.7) and (C.10) we get

$$\begin{aligned} \frac{1}{h}(\mathbf{R}_h - \mathbf{R}) &\longrightarrow 0 \quad \text{strongly in } (L^2(\omega))^{3\times 3}, \\ \frac{1}{h}\left(\frac{\partial \mathcal{V}_h}{\partial s_\alpha} - \mathbf{R}_h \mathbf{t}_\alpha\right) &\longrightarrow 0 \quad \text{strongly in } (L^2(\omega))^3. \end{aligned}$$

We now turn to the estimate of the distance between $\mathbf{R}_h(s_1, s_2)$ and $SO(3)$ for a.e. $(s_1, s_2) \in \omega$. We apply the Poincaré-Wirtinger's inequality to the function $(u_1, u_2) \mapsto \mathbf{R}'(u_1, u_2)$ in the ball $B((s_1, s_2), 3h)$. We obtain

$$\int_{B((s_1, s_2), 3h)} \|\mathbf{R}'(u_1, u_2) - \mathbf{R}'_h(s_1, s_2)\|^2 du_1 du_2 \leq Ch^2 \|\nabla \mathbf{R}'\|_{(L^2(B((s_1, s_2), 3h)))^3}^2$$

where C is the Poincaré-Wirtinger's constant for a ball. Since the open set ω is boundy with a Lipschitz boundary, there exists a positive constant $c(\omega)$, which depends only on ω , such that

$$|(B((s_1, s_2), 3h) \setminus B((s_1, s_2), 2h)) \cap \omega| \geq c(\omega)h^2.$$

Setting $m_h(s_1, s_2)$ the essential infimum of the function $(u_1, u_2) \mapsto \|\mathbf{R}(u_1, u_2) - \mathbf{R}'_h(s_1, s_2)\|$ into the set $(B((s_1, s_2), 3h) \setminus B((s_1, s_2), 2h)) \cap \omega$, we then obtain

$$c(\omega)h^2 m_h(s_1, s_2)^2 \leq Ch^2 \|\nabla \mathbf{R}'\|_{(L^2(B((s_1, s_2), 3h)))^3}^2$$

Hence, thanks to the strong convergence of \mathbf{R}'_h given by (C.9), the above inequality shows that there exists h'_0 which does not depend on $(s_1, s_2) \in \bar{\omega}$ such that for any $h \leq h'_0$

$$\text{dist}(\mathbf{R}'_h(s_1, s_2), SO(3)) \leq 1/8 \quad \text{for any } (s_1, s_2) \in \bar{\omega}.$$

Now,

- in the case $\text{dist}((s_1, s_2), \gamma_0) > 2h$, $(s_1, s_2) \in \omega$, by definition of \mathbf{R}_h and thanks to the above inequality we have $\text{dist}(\mathbf{R}_h(s_1, s_2), SO(3)) \leq 1/8$,

- in the case $\text{dist}((s_1, s_2), \gamma_0) < h$, $(s_1, s_2) \in \omega$, by definition of \mathbf{R}_h we have $\mathbf{R}_h(s_1, s_2) = \mathbf{I}_3$ and then $\text{dist}(\mathbf{R}_h(s_1, s_2), SO(3)) = 0$,

- in the case $h \leq \text{dist}((s_1, s_2), \gamma_0) \leq 2h$, $(s_1, s_2) \in \omega$, due to the fact that $\mathbf{R}' = \mathbf{I}_3$ onto γ_0 , firstly we have

$$\|\mathbf{R}' - \mathbf{I}_3\|_{(L^2(\omega_{6h, \gamma_0}))^{3 \times 3}}^2 \leq Ch^2 \|\nabla \mathbf{R}'\|_{(L^2(\omega_{6h, \gamma_0}))^{3 \times 3}}^2$$

where $\omega_{kh, \gamma_0} = \{(s_1, s_2) \in \mathbb{R}^2 \mid \text{dist}((s_1, s_2), \gamma_0) \leq kh\}$, $k \in \mathbb{N}^*$. Hence

$$\|\mathbf{R}'_h - \mathbf{I}_3\|_{(L^2(\omega_{3h, \gamma_0}))^{3 \times 3}}^2 \leq Ch^2 \|\nabla \mathbf{R}'\|_{(L^2(\omega_{6h, \gamma_0}))^{3 \times 3}}^2.$$

The constants depend only on $\partial\omega$.

Secondly, we set M_h the maximum of the function $(u_1, u_2) \mapsto \|\mathbf{I}_3 - \mathbf{R}'_h(u_1, u_2)\|$ into the closed set $\{(u_1, u_2) \in \omega \mid h \leq \text{dist}((u_1, u_2), \gamma_0) \leq 2h\}$, and let (s_1, s_2) be in this closed subset of ω such that

$$M_h = \|\mathbf{I}_3 - \mathbf{R}'_h(s_1, s_2)\|.$$

Applying the Poincaré-Wirtinger's inequality in the ball $B((s_1, s_2), 4h)$ we deduce that

$$\forall (s'_1, s'_2) \in B((s_1, s_2), h), \quad \|\mathbf{R}'_h(s'_1, s'_2) - \mathbf{R}'_h(s_1, s_2)\| \leq C \|\nabla \mathbf{R}'\|_{(L^2(B((s_1, s_2), 4h)))^3}.$$

The constant depends only on the Poincaré-Wirtinger's constant for a ball.

If M_h is larger than $C \|\nabla \mathbf{R}'\|_{(L^2(B((s_1, s_2), 4h)))^3}$ we have

$$\begin{aligned} \pi h^2 (M_h - C \|\nabla \mathbf{R}'\|_{(L^2(B((s_1, s_2), 4h)))^3})^2 &\leq \|\mathbf{R}'_h - \mathbf{I}_3\|_{(L^2(B((s_1, s_2), h)))^3}^2 \\ &\leq \|\mathbf{R}'_h - \mathbf{I}_3\|_{(L^2(\omega_{3h, \gamma_0}))^{3 \times 3}}^2 \leq Ch^2 \|\nabla \mathbf{R}'\|_{(L^2(\omega_{6h, \gamma_0}))^{3 \times 3}}^2 \end{aligned}$$

then, in all the cases we obtain

$$M_h \leq C \|\nabla \mathbf{R}'\|_{(L^2(\omega_{6h, \gamma_0}))^{3 \times 3}}.$$

The constant does not depend on h and \mathbf{R}' . The above inequalities show that there exists h''_0 such that for any $h \leq h''_0$

$$\|\mathbf{R}'_h(s_1, s_2) - \mathbf{I}_3\| \leq C \|\nabla \mathbf{R}'\|_{(L^2(\omega_{6h, \gamma_0}))^{3 \times 3}} \leq 1/8 \quad \text{for any } (s_1, s_2) \in \omega \quad \text{such that } h \leq \text{dist}((s_1, s_2), \gamma_0) \leq 2h.$$

By definition of \mathbf{R}_h , that gives $\|\mathbf{R}_h(s_1, s_2) - \mathbf{I}_3\| \leq 1/8$.

Finally, for any $h \leq \max(h'_0, h''_0)$ and for any $(s_1, s_2) \in \bar{\omega}$ we have

$$\text{dist}(\mathbf{R}_h(s_1, s_2), SO(3)) \leq 1/8.$$

Using (C.5) and (C.6) we obtain (recall that $\|\cdot\|_2$ is the euclidian norm in \mathbb{R}^3)

$$\forall (s_1, s_2) \in \omega, \quad \left\| \frac{\partial \mathcal{V}'_h}{\partial s_\alpha}(s_1, s_2) - \mathbf{R}'_h(s_1, s_2) \mathbf{t}_\alpha(s_1, s_2) \right\|_2 \leq Ch \|\phi\|_{(W^{2, \infty}(\omega))^3} + C (\|\mathcal{V}\|_{(H^2(\omega_{3h}))^3} + \|\mathbf{R}'\|_{(H^1(\omega_{3h}))^{3 \times 3}})$$

where $\omega_{3h} = \{(s_1, s_2) \in \mathbb{R}^2 \mid \text{dist}((s_1, s_2), \partial\omega) \leq 3h\}$.

We have

$$\frac{\partial \mathcal{V}_h}{\partial s_\alpha} - \mathbf{R}_h \mathbf{t}_\alpha = (1 - \psi_h) \left(\frac{\partial \mathcal{V}'_h}{\partial s_\alpha} - \mathbf{R}'_h \mathbf{t}_\alpha \right) + \frac{\partial \psi_h}{\partial s_\alpha} (\phi - \mathcal{V}'_h).$$

Thanks to the above inequality, (C.4) and again the estimate of $\|\mathbf{R}'_h - \mathbf{I}_3\|$ in the edge strip $h \leq \text{dist}((s_1, s_2), \gamma_0) \leq 2h$ we obtain for all $(s_1, s_2) \in \omega$

$$\begin{aligned} & \left\| \frac{\partial \mathcal{V}_h}{\partial s_\alpha}(s_1, s_2) - \mathbf{R}_h(s_1, s_2) \mathbf{t}_\alpha(s_1, s_2) \right\|_2 \\ & \leq C(h \|\phi\|_{(W^{2,\infty}(\omega))^3} + \|\mathcal{V}\|_{(H^2(\omega_{3h}))^3} + \|\mathbf{R}'\|_{(H^1(\omega_{3h}))^{3 \times 3}} + \|\phi - \mathcal{V}\|_{(H^2(\omega_{5h, \gamma_0}))^{3 \times 3}}). \end{aligned}$$

The same argument as above imply that there exists $h_0 \leq \max(h'_0, h''_0)$ such that for any $0 < h \leq h_0$ and for any $(s_1, s_2) \in \omega$ we have

$$(C.11) \quad \left\| \frac{\partial \mathcal{V}_h}{\partial s_\alpha}(s_1, s_2) - \mathbf{R}_h(s_1, s_2) \mathbf{t}_\alpha(s_1, s_2) \right\|_2 \leq \frac{1}{8}.$$

From (C.4), (C.5), (C.6) and (C.7) there exists a positive constant C which does not depend on h such that

$$(C.12) \quad \|\mathbf{R}_h\|_{(W^{1,\infty}(\omega))^{3 \times 3}} \leq \frac{C}{h} \{ \|\mathcal{V}\|_{(H^2(\omega))^3} + \|\mathbf{R}\|_{(H^1(\omega))^{3 \times 3}} \}.$$

Now we can choose h in term of δ . We set

$$h = \theta \delta, \quad \delta \in (0, \delta_0]$$

and we fixed θ in order to have $h \leq h_0$ and to obtain the right hand side in (C.12) less than $\frac{1}{4\sqrt{2}c'_1\delta}$ (c'_1 is given by (2.3)). It is well-known that there exists a sequence $(\bar{V}_\delta)_{\delta \in (0, \delta_0]}$ such that $(\mathcal{V}_\delta, \mathbf{R}_\delta, \bar{V}_\delta) \in \mathbb{D}_{\gamma_0}$ and satisfying the convergences in (C.1) and the estimate in (C.3). \square

References

- [1] J.M. Ball, Convexity conditions and existence theorems in nonlinear elasticity. Arch. Ration. Mech. Anal. 63 (1976) 337-403.
- [2] D. Blanchard, A. Gaudiello, G. Griso. Junction of a periodic family of elastic rods with a $3d$ plate. I. J. Math. Pures Appl. (9) 88 (2007), no 1, 149-190.
- [3] D. Blanchard, A. Gaudiello, G. Griso. Junction of a periodic family of elastic rods with a thin plate. II. J. Math. Pures Appl. (9) 88 (2007), no 2, 1-33.
- [4] D. Blanchard, G. Griso. Microscopic effects in the homogenization of the junction of rods and a thin plate. Asympt. Anal. 56 (2008), no 1, 1-36.
- [5] D. Blanchard, G. Griso. Decomposition of deformations of thin rods. Application to nonlinear elasticity, to appear in Analysis and Applications.
- [6] P.G. Ciarlet, Mathematical Elasticity, Vol. I, North-Holland, Amsterdam (1988).
- [7] P.G. Ciarlet, Mathematical Elasticity, Vol. II. Theory of plates. North-Holland, Amsterdam (1997).
- [8] P.G. Ciarlet, Mathematical Elasticity, Vol. III. Theory of shells. North-Holland, Amsterdam (2000).
- [9] P.G. Ciarlet, Un modèle bi-dimensionnel non linéaire de coques analogue à celui de W.T. Koiter, C. R. Acad. Sci. Paris, Sér. I, 331 (2000), 405-410.

- [10] P.G. Ciarlet and C. Mardare, Continuity of a deformation in H^1 as a function of its Cauchy-Green tensor in L^1 . *J. Nonlinear Sci.* 14 (2004), no. 5, 415–427 (2005).
- [11] P.G. Ciarlet and C. Mardare, An introduction to shell theory, *Differential geometry: theory and applications*, 94–184, Ser. Contemp. Appl. Math. CAM, 9, Higher Ed. Press, Beijing, 2008.
- [12] P.G. Ciarlet and P. Destuynder, A justification of a nonlinear model in plate theory. *Comput. Methods Appl. Mech. Eng.* 17/18 (1979) 227-258.
- [13] G. Dal Maso: *An Introduction to Γ -convergence*. Birkhuser, Boston, 1993.
- [14] G. Friesecke, R. D. James and S. Müller. A theorem on geometric rigidity and the derivation of nonlinear plate theory from the three-dimensional elasticity. *Communications on Pure and Applied Mathematics*, Vol. LV, 1461-1506 (2002).
- [15] G. Friesecke, R. D. James and S. Müller, A hierarchy of plate models derived from nonlinear elasticity by Γ -convergence. (2005)
- [16] G. Friesecke, R. D. James, M.G. Mora and S. Müller, Derivation of nonlinear bending theory for shells from three-dimensionnal nonlinear elasticity by Gamma convergence, *C. R. Acad. Sci. Paris, Ser. I* 336 (2003).
- [17] G. Griso. Decomposition of displacements of thin structures. *J. Math. Pures Appl.* 89 (2008) 199-233.
- [18] G. Griso. Asymptotic behavior of curved rods by the unfolding method. *Math. Meth. Appl. Sci.* 2004; 27: 2081-2110.
- [19] G. Griso. Asymptotic behavior of structures made of plates. *Analysis and Applications* 3 (2005), 4, 325-356.
- [20] H. Le Dret and A. Raoult, The nonlinear membrane model as variational limit of nonlinear three-dimensional elasticity. *J. Math. Pures Appl.* 75 (1995) 551-580.
- [21] H. Le Dret and A. Raoult, The quasiconvex envelope of the Saint Venant-Kirchhoff stored energy function. *Proc. R. Soc. Edin., A* 125 (1995) 1179-1192.
- [22] J.E. Marsden and T.J.R. Hughes, *Mathematical Foundations of Elasticity*, Prentice-Hall, Englewood Cliffs, (1983).
- [23] O. Pantz, On the justification of the nonlinear inextensional plate model. *C. R. Acad. Sci. Paris Sér. I Math.* 332 (2001), no. 6, 587–592.
- [24] O. Pantz, On the justification of the nonlinear inextensional plate model. *Arch. Ration. Mech. Anal.* 167 (2003), no. 3, 179–209.