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## The nonlinear membrane energy: Variational derivation under the constraint “ $\det u > 0$ ”

Anza Hafsa, O ; Mandallena, J P

Abstract: Acerbi, Buttazzo and Percivale gave a variational definition of the nonlinear string energy under the constraint “ $\det u > 0$ ” (see [E. Acerbi, G. Buttazzo, D. Percivale, A variational definition of the strain energy for an elastic string, *J. Elasticity* 25 (1991) 137–148]). In the same spirit, we obtain the nonlinear membrane energy under the simpler constraint “ $\det u > 0$ ”.

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**THE NONLINEAR MEMBRANE ENERGY: VARIATIONAL  
DERIVATION UNDER THE CONSTRAINT “ $\det \nabla u > 0$ ”**

OMAR ANZA HAFSA AND JEAN-PHILIPPE MANDALLENA

ABSTRACT. In [4] we gave a variational definition of the nonlinear membrane energy under the constraint “ $\det \nabla u \neq 0$ ”. In this paper we obtain the nonlinear membrane energy under the more realistic constraint “ $\det \nabla u > 0$ ”.

1. INTRODUCTION

Consider an elastic material occupying in a reference configuration the bounded open set  $\Sigma_\varepsilon \subset \mathbb{R}^3$  given by

$$\Sigma_\varepsilon := \Sigma \times \left] -\frac{\varepsilon}{2}, \frac{\varepsilon}{2} \right[ ,$$

where  $\varepsilon > 0$  is very small and  $\Sigma \subset \mathbb{R}^2$  is Lipschitz, open and bounded. A point of  $\Sigma_\varepsilon$  is denoted by  $(x, x_3)$  with  $x \in \Sigma$  and  $x_3 \in ]-\frac{\varepsilon}{2}, \frac{\varepsilon}{2}[$ . Let  $W : \mathbb{M}^{3 \times 3} \rightarrow [0, +\infty]$  be the stored-energy function supposed to be *continuous* and *coercive*, i.e.,  $W(F) \geq C|F|^p$  for all  $F \in \mathbb{M}^{3 \times 3}$  and some  $C > 0$ . In order to take into account the important physical properties that the interpenetration of matter does not occur and that an infinite amount of energy is required to compress a finite volume into zero volume, i.e.,

$$W(F) \rightarrow +\infty \text{ as } \det F \rightarrow 0,$$

where  $\det F$  denotes the determinant of the  $3 \times 3$  matrix  $F$ , we assume that:

- (1)  $W(F) = +\infty$  if and only if  $\det F \leq 0$ ;
- (2) for every  $\delta > 0$ , there exists  $c_\delta > 0$  such that for all  $F \in \mathbb{M}^{3 \times 3}$ ,  
if  $\det F \geq \delta$  then  $W(F) \leq c_\delta(1 + |F|^p)$ .

Our goal is to show that as  $\varepsilon \rightarrow 0$  the three-dimensional free energy functional  $E_\varepsilon : W^{1,p}(\Sigma_\varepsilon; \mathbb{R}^3) \rightarrow [0, +\infty]$  (with  $p > 1$ ) defined by

$$(3) \quad E_\varepsilon(u) := \frac{1}{\varepsilon} \int_{\Sigma_\varepsilon} W(\nabla u(x, x_3)) dx dx_3$$

converges in a variational sense (see Definition 2.1) to the two-dimensional free energy functional  $E_{\text{mem}} : W^{1,p}(\Sigma; \mathbb{R}^3) \rightarrow [0, +\infty]$  given by

$$(4) \quad E_{\text{mem}}(v) := \int_{\Sigma} W_{\text{mem}}(\nabla v(x)) dx$$

with  $W_{\text{mem}} : \mathbb{M}^{3 \times 2} \rightarrow [0, +\infty]$ . Usually,  $E_{\text{mem}}$  is called the nonlinear membrane energy associated with the two-dimensional elastic material with respect to the reference configuration  $\Sigma$ . Furthermore we wish to give a representation formula for  $W_{\text{mem}}$ .

To our knowledge, the problem of giving a variational definition of the nonlinear membrane energy was studied for the first time by Percivale in [18]. His paper deals with the constraint “ $\det \nabla u > 0$ ” but seems to contain some mistakes (it never was published). Nevertheless, Percivale introduced the “good” formula for  $W_{\text{mem}}$ , i.e.,  $W_{\text{mem}} = \mathcal{Q}W_0$  where  $W_0$  is given by (5) and  $\mathcal{Q}W_0$  denotes the quasiconvex envelope of  $W_0$ . Then, in [17] Le Dret and Raoult gave a complete proof of percivale’s conjecture in the simpler case where  $W$  is of  $p$ -polynomial growth, i.e.,  $W(F) \leq c(1 + |F|^p)$  for all  $F \in \mathbb{M}^{3 \times 3}$  and some  $c > 0$ . Although the  $p$ -polynomial growth case is not compatible with (1) and (2) their paper established a suitable framework to deal with dimensional reduction problems (it is the point of departure of many works on the subject). After Percivale, Ben Belgacem also considered the constraint “ $\det \nabla u > 0$ ”. In [8, Theorem 1] he announced to have succeed to handle (1) and (2). In [9], which is the paper corresponding to the note [8], the statement [8, Theorem 1] is partly proved (however, a more detailed proof, but not fully complete, can be found in his thesis [7]). Moreover, for Ben Belgacem  $W_{\text{mem}} = \mathcal{Q}\mathcal{R}W_0$  where  $\mathcal{R}W_0$  denotes the rank one convex envelope of  $W_0$  (in fact, as we proved in [3, 4],  $\mathcal{Q}\mathcal{R}W_0 = \mathcal{Q}W_0$ ). Nevertheless, Ben Belgacem’s thesis highlighted the role of approximation theorems for Sobolev functions by smooth immersions in the studying of the passage 3D-2D in presence of (1) and (2). Recently, in [4] we gave a variational definition of the nonlinear membrane energy under the constraint “ $\det \nabla u \neq 0$ ”. In the present paper, using the same method as in [4] and some results of Ben Belgacem’s thesis (mainly, Theorem A.1 and Lemma 5.4), we obtain the nonlinear membrane energy under the more realistic constraint “ $\det \nabla u > 0$ ”.

An outline of the paper is as follows. The variational convergence of  $E_\varepsilon$  to  $E_{\text{mem}}$  as  $\varepsilon \rightarrow 0$  as well as a representation formula for  $W_{\text{mem}}$  are given by Corollary 2.9 in Sect. 2.4. Corollary 2.9 is a consequence of Theorems 2.5, 2.6 and 2.8. Roughly, Theorems 2.5 and 2.6 establish the existence of the variational limit of  $E_\varepsilon$  as  $\varepsilon \rightarrow 0$  (see Sect. 2.2), and Theorem 2.8 gives an integral representation for the corresponding variational limit, and so a representation formula for  $W_{\text{mem}}$  (see Sect. 2.3). In fact, Theorem 2.8 is obtained from Theorem 2.6 which furnishes a “simplified” formula for the variational limit.

Theorem 2.5 is proved in Section 4. The principal ingredients are Theorem 2.6 and Theorem 3.4 whose proof (given in Section 3) uses an interchange theorem of infimum and integral that we obtained in [2]. (Note that the techniques used to prove Theorems 2.5 and 3.4 are the same as in [4, Sections 3 and 4].)

Theorem 2.6 is proved in Section 5. The main arguments are two approximation theorems developed by Ben Belgacem-Bennequin (see [7]) and Gromov-Eliashberg (see [14]). These theorems are stated in Appendix A.

Theorem 2.8 is proved in [4, Appendix A] (see also [3]).

## 2. RESULTS

**2.1. Variational convergence.** To accomplish our asymptotic analysis, we use the notion of convergence introduced by Anzellotti, Baldo and Percivale in [5] in order to deal with dimension reduction problems in mechanics. Let  $\pi = \{\pi_\varepsilon\}_\varepsilon$  be the family of maps  $\pi_\varepsilon : W^{1,p}(\Sigma_\varepsilon; \mathbb{R}^3) \rightarrow W^{1,p}(\Sigma; \mathbb{R}^3)$  defined by

$$\pi_\varepsilon(u) := \frac{1}{\varepsilon} \int_{-\frac{\varepsilon}{2}}^{\frac{\varepsilon}{2}} u(\cdot, x_3) dx_3.$$

**Definition 2.1.** We say that  $E_\varepsilon$   $\Gamma(\pi)$ -converges to  $E_{\text{mem}}$  as  $\varepsilon \rightarrow 0$ , and we write  $E_{\text{mem}} = \Gamma(\pi)\text{-}\lim_{\varepsilon \rightarrow 0} E_\varepsilon$ , if the following two assertions hold:

- (i) for all  $v \in W^{1,p}(\Sigma; \mathbb{R}^3)$  and all  $\{u_\varepsilon\}_\varepsilon \subset W^{1,p}(\Sigma_\varepsilon; \mathbb{R}^3)$ ,  
if  $\pi_\varepsilon(u_\varepsilon) \rightarrow v$  in  $L^p(\Sigma; \mathbb{R}^3)$  then  $E_{\text{mem}}(v) \leq \liminf_{\varepsilon \rightarrow 0} E_\varepsilon(u_\varepsilon)$ ;
- (ii) for all  $v \in W^{1,p}(\Sigma; \mathbb{R}^3)$ , there exists  $\{u_\varepsilon\}_\varepsilon \subset W^{1,p}(\Sigma_\varepsilon; \mathbb{R}^3)$  such that:  
 $\pi_\varepsilon(u_\varepsilon) \rightarrow v$  in  $L^p(\Sigma; \mathbb{R}^3)$  and  $E_{\text{mem}}(v) \geq \limsup_{\varepsilon \rightarrow 0} E_\varepsilon(u_\varepsilon)$ .

In fact, Definition 2.1 is a variant of De Giorgi's  $\Gamma$ -convergence. This is made clear by Lemma 2.3. Consider  $\mathcal{E}_\varepsilon : W^{1,p}(\Sigma; \mathbb{R}^3) \rightarrow [0, +\infty]$  defined by

$$\mathcal{E}_\varepsilon(v) := \inf \left\{ E_\varepsilon(u) : \pi_\varepsilon(u) = v \right\}.$$

**Definition 2.2.** We say that  $\mathcal{E}_\varepsilon$   $\Gamma$ -converges to  $E_{\text{mem}}$  as  $\varepsilon \rightarrow 0$ , and we write  $E_{\text{mem}} = \Gamma\text{-}\lim_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon$  if for every  $v \in W^{1,p}(\Sigma; \mathbb{R}^3)$ ,

$$\left( \Gamma\text{-}\liminf_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon \right) (v) = \left( \Gamma\text{-}\limsup_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon \right) (v) = E_{\text{mem}}(v),$$

where  $(\Gamma\text{-}\liminf_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon)(v) := \inf \left\{ \liminf_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon(v_\varepsilon) : v_\varepsilon \rightarrow v \text{ in } L^p(\Sigma; \mathbb{R}^3) \right\}$  and  $(\Gamma\text{-}\limsup_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon)(v) := \inf \left\{ \limsup_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon(v_\varepsilon) : v_\varepsilon \rightarrow v \text{ in } L^p(\Sigma; \mathbb{R}^3) \right\}$ .

For a deeper discussion of the  $\Gamma$ -convergence theory we refer to the book [11]. Clearly, Definition 2.2 is equivalent to assertions (i) and (ii) in definition 2.1 with " $\pi(u_\varepsilon) \rightarrow v$ " replaced by " $v_\varepsilon \rightarrow v$ ". It is then obvious that

**Lemma 2.3.**  $E_{\text{mem}} = \Gamma(\pi)\text{-}\lim_{\varepsilon \rightarrow 0} E_\varepsilon$  if and only if  $E_{\text{mem}} = \Gamma\text{-}\lim_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon$ .

The  $\Gamma(\pi)$ -convergence of  $E_\varepsilon$  in (3) to  $E_{\text{mem}}$  in (4) as  $\varepsilon \rightarrow 0$  as well as a representation formula for  $W_{\text{mem}}$  are given by Corollary 2.9. It is a consequence of Theorems 2.5, 2.6 and 2.8. Roughly, Theorems 2.5 and 2.6 establish the existence of the  $\Gamma(\pi)$ -limit of  $E_\varepsilon$  as  $\varepsilon \rightarrow 0$  (see Sect. 2.2), and Theorem 2.8 gives an integral representation for the corresponding  $\Gamma(\pi)$ -limit, and so a representation formula for  $W_{\text{mem}}$  (see Sect. 2.3).

**2.2.  $\Gamma$ -convergence of  $\mathcal{E}_\varepsilon$  as  $\varepsilon \rightarrow 0$ .** Denote by  $C^1(\overline{\Sigma}; \mathbb{R}^3)$  the space of all restrictions to  $\overline{\Sigma}$  of  $C^1$ -differentiable functions from  $\mathbb{R}^2$  to  $\mathbb{R}^3$ , and set

$$C_*^1(\overline{\Sigma}; \mathbb{R}^3) := \left\{ v \in C^1(\overline{\Sigma}; \mathbb{R}^3) : \partial_1 v(x) \wedge \partial_2 v(x) \neq 0 \text{ for all } x \in \overline{\Sigma} \right\},$$

where  $\partial_1 v(x)$  (resp.  $\partial_2 v(x)$ ) denotes the partial derivative of  $v$  at  $x = (x_1, x_2)$  with respect to  $x_1$  (resp.  $x_2$ ). (In fact,  $C_*^1(\overline{\Sigma}; \mathbb{R}^3)$  is the set of all  $C^1$ -immersions from  $\overline{\Sigma}$  to  $\mathbb{R}^3$ .) Let  $\mathcal{E} : W^{1,p}(\Sigma; \mathbb{R}^3) \rightarrow [0, +\infty]$  be defined by

$$\mathcal{E}(v) := \begin{cases} \int_{\Sigma} W_0(\nabla v(x)) dx & \text{if } v \in C_*^1(\overline{\Sigma}; \mathbb{R}^3) \\ +\infty & \text{otherwise,} \end{cases}$$

where  $W_0 : \mathbb{M}^{3 \times 2} \rightarrow [0, +\infty]$  is given by

$$(5) \quad W_0(\xi) := \inf_{\zeta \in \mathbb{R}^3} W(\xi \mid \zeta)$$

with  $(\xi \mid \zeta)$  denoting the element of  $\mathbb{M}^{3 \times 3}$  corresponding to  $(\xi, \zeta) \in \mathbb{M}^{3 \times 2} \times \mathbb{R}^3$ . (As  $W$  is coercive, it is easy to see that  $W_0$  is coercive, i.e.,  $W_0(\xi) \geq C|\xi|^p$  for all  $\xi \in \mathbb{M}^{3 \times 2}$  and some  $C > 0$ .) The following lemma gives three elementary properties

of  $W_0$  (the proof is left to the reader). Note that conditions (1) and (2) imply  $W_0$  is not of  $p$ -polynomial growth.

**Lemma 2.4.** *Denote by  $\xi_1 \wedge \xi_2$  the cross product of vectors  $\xi_1, \xi_2 \in \mathbb{R}^3$ .*

- (i)  $W_0$  is continuous.
  - (ii) If (1) holds then  $W_0(\xi_1 \mid \xi_2) = +\infty$  if and only if  $\xi_1 \wedge \xi_2 = 0$ .
  - (iii) If (2) holds then:
- (6) for all  $\delta > 0$ , there exists  $c_\delta > 0$  such that for all  $\xi = (\xi_1 \mid \xi_2) \in \mathbb{M}^{3 \times 2}$ ,  
if  $|\xi_1 \wedge \xi_2| \geq \delta$  then  $W_0(\xi) \leq c_\delta(1 + |\xi|^p)$ .

Taking Lemma 2.3 into account, we see that the existence of the  $\Gamma(\pi)$ -limit of  $E_\varepsilon$  as  $\varepsilon \rightarrow 0$  follows from Theorem 2.5.

**Theorem 2.5.** *Let assumptions (1) and (2) hold. Then  $\Gamma\text{-}\lim_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon = \bar{\mathcal{E}}$  with  $\bar{\mathcal{E}} : W^{1,p}(\Sigma; \mathbb{R}^3) \rightarrow [0, +\infty]$  given by*

$$\bar{\mathcal{E}}(v) := \inf \left\{ \liminf_{n \rightarrow +\infty} \mathcal{E}(v_n) : W^{1,p}(\Sigma; \mathbb{R}^3) \ni v_n \rightarrow v \text{ in } L^p(\Sigma; \mathbb{R}^3) \right\}.$$

The proof of Theorem 2.5 is established in Section 4. It uses Theorem 3.4 (see Section 3) and Theorem 2.6.

**Theorem 2.6.** *If (6) holds then  $\bar{\mathcal{E}}(v) = \mathcal{I}(v)$  for all  $v \in W^{1,p}(\Sigma; \mathbb{R}^3)$ , where  $\mathcal{I} : W^{1,p}(\Sigma; \mathbb{R}^3) \rightarrow [0, +\infty]$  is given by*

$$\mathcal{I}(v) := \inf \left\{ \liminf_{n \rightarrow +\infty} \int_{\Sigma} W_0(\nabla v_n(x)) dx : W^{1,p}(\Sigma; \mathbb{R}^3) \ni v_n \rightarrow v \text{ in } L^p(\Sigma; \mathbb{R}^3) \right\}.$$

Theorem 2.6 is proved in Section 6 by using two approximation theorems developed by Ben Belgacem-Bennequin (see [7]) and Gromov-Eliashberg (see [14]). These theorems are stated in Appendix A.

**2.3. Integral representation of  $\mathcal{I}$ .** From now on, given a bounded open set  $D \subset \mathbb{R}^2$  with  $|\partial D| = 0$ , we denote by  $\text{Aff}(D; \mathbb{R}^3)$  the space of all continuous piecewise affine functions from  $D$  to  $\mathbb{R}^3$ , i.e.,  $v \in \text{Aff}(D; \mathbb{R}^3)$  if and only if  $v$  is continuous and there exists a finite family  $(D_i)_{i \in I}$  of open disjoint subsets of  $D$  such that  $|\partial D_i| = 0$  for all  $i \in I$ ,  $|D \setminus \cup_{i \in I} D_i| = 0$  and for every  $i \in I$ ,  $\nabla v(x) = \xi_i$  in  $D_i$  with  $\xi_i \in \mathbb{M}^{3 \times 2}$  (where  $|\cdot|$  denotes the Lebesgue measure in  $\mathbb{R}^2$ ). Define  $\mathcal{Z}W_0 : \mathbb{M}^{3 \times 2} \rightarrow [0, +\infty]$  by

$$(7) \quad \mathcal{Z}W_0(\xi) := \inf \left\{ \int_Y W_0(\xi + \nabla \phi(y)) dy : \phi \in \text{Aff}_0(Y; \mathbb{R}^3) \right\}$$

where  $Y := ]0, 1[$  and  $\text{Aff}_0(Y; \mathbb{R}^3) := \{\phi \in \text{Aff}(Y; \mathbb{R}^3) : \phi = 0 \text{ on } \partial Y\}$ . (As  $W_0$  is coercive, it is easy to see that  $\mathcal{Z}W_0$  is coercive.) Recall the definitions of quasiconvexity and quasiconvex envelope:

**Definition 2.7.** Let  $f : \mathbb{M}^{3 \times 2} \rightarrow [0, +\infty]$  be a Borel measurable function.

- (i) We say that  $f$  is quasiconvex if for every  $\xi \in \mathbb{M}^{3 \times 2}$ , every bounded open set  $D \subset \mathbb{R}^2$  with  $|\partial D| = 0$  and every  $\phi \in W_0^{1,\infty}(D; \mathbb{R}^3)$ ,

$$f(\xi) \leq \frac{1}{|D|} \int_D f(\xi + \nabla \phi(x)) dx.$$

- (ii) By the quasiconvex envelope of  $f$ , we mean the unique function (when it exists)  $\mathcal{Q}f : \mathbb{M}^{3 \times 2} \rightarrow [0, +\infty]$  such that:

- $\mathcal{Q}f$  is Borel measurable, quasiconvex and  $\mathcal{Q}f \leq f$ ;
- for all  $g : \mathbb{M}^{3 \times 2} \rightarrow [0, +\infty]$ , if  $g$  is Borel measurable, quasiconvex and  $g \leq f$ , then  $g \leq \mathcal{Q}f$ .

(Usually, for simplicity, we say that  $\mathcal{Q}f$  is the greatest quasiconvex function which less than or equal to  $f$ .)

Under (6), we proved that  $\mathcal{Z}W_0$  is of  $p$ -polynomial growth and so continuous (see [4, Propositions A.3 and A.1(iii)]) and that  $\mathcal{Z}W_0$  is the quasiconvex envelope of  $W_0$ , i.e.,  $\mathcal{Z}W_0 = \mathcal{Q}W_0$  (see [4, Proposition A.5]). Taking Theorems 2.5 and 2.6 together with Lemmas 2.3 and 2.4(iii) into account, we see that Theorem 2.8 gives an integral representation for the  $\Gamma(\pi)$ -limit of  $E_\varepsilon$  as  $\varepsilon \rightarrow 0$  as well as a representation formula for  $W_{\text{mem}}$ .

**Theorem 2.8.** *If (6) holds then for every  $v \in W^{1,p}(\Sigma; \mathbb{R}^3)$ ,*

$$\mathcal{I}(v) = \int_{\Sigma} \mathcal{Q}W_0(\nabla v(x)) dx.$$

Theorem 2.8 is proved in [4, Appendix A] (see also [3]).

**2.4.  $\Gamma(\pi)$ -convergence of  $E_\varepsilon$  to  $E_{\text{mem}}$  as  $\varepsilon \rightarrow 0$ .** According to Lemmas 2.3 and Lemma 2.4(iii), a direct consequence of Theorems 2.5, 2.6 and 2.8 is the following.

**Corollary 2.9.** *Let assumptions (1) and (2) hold. Then as  $\varepsilon \rightarrow 0$ ,  $E_\varepsilon$  in (3)  $\Gamma(\pi)$ -converge to  $E_{\text{mem}}$  in (4) with  $W_{\text{mem}} = \mathcal{Q}W_0$ .*

*Remark 2.10.* Corollary 2.9 can be applied when  $W : \mathbb{M}^{3 \times 3} \rightarrow [0, +\infty]$  is given by

$$W(F) := h(\det F) + |F|^p,$$

where  $h : \mathbb{R} \rightarrow [0, +\infty]$  is a continuous function such that:

- $h(t) = +\infty$  if and only if  $t \leq 0$ ;
- for every  $\delta > 0$ , there exists  $r_\delta > 0$  such that  $h(t) \leq r_\delta$  for all  $t \geq \delta$ .

### 3. REPRESENTATION OF $\mathcal{E}$

The goal of this section is to show Theorem 3.4. To this end, we begin by proving two lemmas.

For every  $v \in C_*^1(\overline{\Sigma}; \mathbb{R}^3)$  and  $j \geq 1$ , we define the multifunction  $\Lambda_v^j : \overline{\Sigma} \rightrightarrows \mathbb{R}^3$  by

$$\Lambda_v^j(x) := \left\{ \zeta \in \mathbb{R}^3 : \det(\nabla v(x) \mid \zeta) \geq \frac{1}{j} \right\}.$$

**Lemma 3.1.** *Let  $v \in C_*^1(\overline{\Sigma}; \mathbb{R}^3)$ . Then:*

- (i) *for every  $j \geq 1$ ,  $\Lambda_v^j$  is a nonempty convex closed-valued lower semicontinuous<sup>1</sup> multifunction;*
- (ii) *for every  $x \in \overline{\Sigma}$ ,  $\Lambda_v^1(x) \subset \cdots \subset \Lambda_v^j(x) \subset \cdots \subset \cup_{j \geq 1} \Lambda_v^j(x) = \Lambda_v(x)$ , where  $\Lambda_v(x) := \{\zeta \in \mathbb{R}^3 : \det(\nabla v(x) \mid \zeta) > 0\}$ .*

<sup>1</sup>A multifunction  $\Lambda : \overline{\Sigma} \rightarrow \mathbb{R}^3$  is said to be lower semicontinuous if for every closed subset  $X$  of  $\mathbb{R}^3$ , every  $x \in \overline{\Sigma}$  and every  $\{x_n\}_{n \geq 1} \subset \overline{\Sigma}$  such that  $|x_n - x| \rightarrow 0$  as  $n \rightarrow +\infty$  and  $\Lambda(x_n) \subset X$  for all  $n \geq 1$ , we have  $\Lambda(x) \subset X$  (see [6] for more details).

*Proof.* (ii) is obvious. Prove then (i). Let  $j \geq 1$ . It is easy to see that for every  $x \in \overline{\Sigma}$ ,  $\Lambda_v^j(x)$  is nonempty, convex and closed. Let  $X$  be a closed subset of  $\mathbb{R}^3$ , let  $x \in \overline{\Sigma}$ , and let  $\{x_n\}_{n \geq 1} \subset \overline{\Sigma}$  such that  $|x_n - x| \rightarrow 0$  as  $n \rightarrow +\infty$  and  $\Lambda_v^j(x_n) \subset X$  for all  $n \geq 1$ . Let  $\zeta \in \Lambda_v^j(x)$  and let  $\{\zeta_m\}_{m \geq 1} \subset \mathbb{R}^3$  be given by  $\zeta_m := \zeta + \frac{1}{m}\zeta$ . Then, for every  $m \geq 1$ ,

$$(8) \quad \det(\nabla v(x) \mid \zeta_m) = \det(\nabla v(x) \mid \zeta) + \frac{1}{m} \det(\nabla v(x) \mid \zeta) \geq \frac{1}{j} + \frac{1}{mj}.$$

Fix any  $m \geq 1$ . Since  $\det(\nabla v(x_n) \mid \zeta_m) \rightarrow \det(\nabla v(x) \mid \zeta_m)$  as  $n \rightarrow +\infty$ , using (8) we see that  $\det(\nabla v(x_{n_0}) \mid \zeta_m) > \frac{1}{j}$  for some  $n_0 \geq 1$ , so that  $\zeta_m \in \Lambda_v^j(x_{n_0})$ . Thus  $\zeta_m \in X$  for all  $m \geq 1$ . As  $X$  is closed we have  $\zeta = \lim_{m \rightarrow +\infty} \zeta_m \in X$ .  $\square$

In the sequel, given  $\Lambda : \overline{\Sigma} \rightrightarrows \mathbb{R}^3$  we set

$$C(\overline{\Sigma}; \Lambda) := \left\{ \phi \in C(\overline{\Sigma}; \mathbb{R}^3) : \phi(x) \in \Lambda(x) \text{ for all } x \in \overline{\Sigma} \right\},$$

where  $C(\overline{\Sigma}; \mathbb{R}^3)$  denotes the space of all continuous functions from  $\overline{\Sigma}$  to  $\mathbb{R}^3$ .

**Lemma 3.2.** *Given  $v \in C_*^1(\Sigma; \mathbb{R}^3)$  and  $j \geq 1$ , if (2) holds, then*

$$\inf_{\phi \in C(\overline{\Sigma}; \Lambda_v^j)} \int_{\Sigma} W(\nabla v(x) \mid \phi(x)) dx = \int_{\Sigma} \inf_{\zeta \in \Lambda_v^j(x)} W(\nabla v(x) \mid \zeta) dx.$$

To prove Lemma 3.2 we need the following interchange theorem of infimum and integral (that we proved in [2, Corollary 5.4]).

**Theorem 3.3.** *Let  $\Gamma : \overline{\Sigma} \rightrightarrows \mathbb{R}^3$  and let  $f : \overline{\Sigma} \times \mathbb{R}^3 \rightarrow [0, +\infty]$ . Assume that:*

- (H<sub>1</sub>) *f is a Carathéodory integrand;*
- (H<sub>2</sub>)  *$\Gamma$  is a nonempty convex closed-valued lower semicontinuous multifunction;*
- (H<sub>3</sub>)  *$C(\overline{\Sigma}; \Gamma) \neq \emptyset$  and for every  $\phi, \hat{\phi} \in C(\overline{\Sigma}; \Gamma)$ ,*

$$\int_{\Sigma} \max_{\alpha \in [0,1]} f(x, \alpha\phi(x) + (1-\alpha)\hat{\phi}(x)) dx < +\infty.$$

Then,

$$\inf_{\phi \in C(\overline{\Sigma}; \Gamma)} \int_{\Sigma} f(x, \phi(x)) dx = \int_{\Sigma} \inf_{\zeta \in \Gamma(x)} f(x, \zeta) dx.$$

*Proof of Lemma 3.2.* Since  $W$  is continuous, (H<sub>1</sub>) holds with  $f(x, \zeta) = W(\nabla v(x) \mid \zeta)$ . Lemma 3.1 shows that (H<sub>2</sub>) is satisfied with  $\Gamma = \Lambda_v^j$ , and  $C(\overline{\Sigma}; \Lambda_v^j) \neq \emptyset$  (for example  $\Phi : \overline{\Sigma} \rightarrow \mathbb{R}^3$  defined by (12) belongs to  $C(\overline{\Sigma}; \Lambda_v^j)$ ). Given  $\phi, \hat{\phi} \in C(\overline{\Sigma}; \Lambda_v^j)$ , it is clear that  $\det(\nabla v(x) \mid \alpha\phi(x) + (1-\alpha)\hat{\phi}(x)) \geq 1/j$  for all  $\alpha \in [0, 1]$  and all  $x \in \overline{\Sigma}$ . By (2) there exists  $c > 0$  depending only on  $j, v, \phi$  and  $\hat{\phi}$  such that  $W(\nabla v(x) \mid \alpha\phi(x) + (1-\alpha)\hat{\phi}(x)) \leq c$  for all  $x \in \overline{\Sigma}$ . Thus (H<sub>3</sub>) is verified with  $f(x, \zeta) = W(\nabla v(x) \mid \zeta)$  and  $\Gamma = \Lambda_v^j$ , and Lemma 3.2 follows from Lemma 3.3.  $\square$

Here is our (non integral) representation theorem for  $\mathcal{E}$ .

**Theorem 3.4.** *If (1) and (2) hold, then for every  $v \in C_*^1(\overline{\Sigma}; \mathbb{R}^3)$ ,*

$$(9) \quad \mathcal{E}(v) = \inf_{j \geq 1} \inf_{\phi \in C(\overline{\Sigma}; \Lambda_v^j)} \int_{\Sigma} W(\nabla v(x) \mid \phi(x)) dx.$$

*Proof.* Fix  $v \in C_*^1(\overline{\Sigma}; \mathbb{R}^3)$  and denote by  $\hat{\mathcal{E}}(v)$  the right-hand side of (9). It is easy to verify that  $\mathcal{E}(v) \leq \hat{\mathcal{E}}(v)$ . We are thus reduced to prove that

$$(10) \quad \hat{\mathcal{E}}(v) \leq \mathcal{E}(v).$$

Using Lemma 3.2, we obtain

$$(11) \quad \hat{\mathcal{E}}(v) \leq \inf_{j \geq 1} \int_{\Sigma} \inf_{\zeta \in \Lambda_v^j(x)} W(\nabla v(x) \mid \zeta) dx.$$

Consider the continuous function  $\Phi : \overline{\Sigma} \rightarrow \mathbb{R}^3$  defined by

$$(12) \quad \Phi(x) := \frac{\partial_1 v(x) \wedge \partial_2 v(x)}{|\partial_1 v(x) \wedge \partial_2 v(x)|^2}.$$

Then,  $\det(\nabla v(x) \mid \Phi(x)) = 1$  for all  $x \in \overline{\Sigma}$ . Using (2) we deduce that there exists  $c > 0$  depending only on  $p$  such that

$$\int_{\Sigma} \inf_{\zeta \in \Lambda_v^1(x)} W(\nabla v(x) \mid \zeta) dx \leq c(|\Sigma| + \|\nabla v\|_{L^p(\Sigma; \mathbb{M}^{3 \times 2})}^p + \|\Phi\|_{L^p(\Sigma; \mathbb{R}^3)}^p).$$

It follows that  $\inf_{\zeta \in \Lambda_v^1(\cdot)} W(\nabla v(\cdot) \mid \zeta) \in L^1(\Sigma)$ . From Lemma 3.1(i) and (ii), we see that  $\{\inf_{\zeta \in \Lambda_v^j(\cdot)} W(\nabla v(\cdot) \mid \zeta)\}_{j \geq 1}$  is non-increasing, and that for every  $x \in \overline{\Sigma}$ ,

$$(13) \quad \inf_{j \geq 1} \inf_{\zeta \in \Lambda_v^j(x)} W(\nabla v(x) \mid \zeta) = W_0(\nabla v(x)),$$

and (23) follows from (11) and (13) by using Lebesgue's dominated convergence theorem.  $\square$

#### 4. EXISTENCE OF $\Gamma$ - $\lim_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon$

In this section we prove Theorem 2.5. Since  $\Gamma\text{-}\liminf_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon \leq \Gamma\text{-}\limsup_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon$ , we only need to show that:

- (a)  $\overline{\mathcal{E}} \leq \Gamma\text{-}\liminf_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon$ ;
- (b)  $\Gamma\text{-}\limsup_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon \leq \overline{\mathcal{E}}$ .

In the sequel, we follow the notation used in Section 3.

**4.1. Proof of (a).** Let  $v \in W^{1,p}(\Sigma; \mathbb{R}^3)$  and let  $\{v_\varepsilon\}_\varepsilon \subset W^{1,p}(\Sigma; \mathbb{R}^3)$  be such that  $v_\varepsilon \rightarrow v$  in  $L^p(\Sigma; \mathbb{R}^3)$ . We have to prove that

$$(14) \quad \liminf_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon(v_\varepsilon) \geq \overline{\mathcal{E}}(v).$$

Without loss of generality we can assume that  $\sup_{\varepsilon > 0} \mathcal{E}_\varepsilon(v_\varepsilon) < +\infty$ . To every  $\varepsilon > 0$  there corresponds  $u_\varepsilon \in \pi_\varepsilon^{-1}(v_\varepsilon)$  such that

$$(15) \quad \mathcal{E}_\varepsilon(v_\varepsilon) \geq E_\varepsilon(u_\varepsilon) - \varepsilon.$$

Defining  $\hat{u}_\varepsilon : \Sigma_1 \rightarrow \mathbb{R}^3$  by  $\hat{u}_\varepsilon(x, x_3) := u_\varepsilon(x, \varepsilon x_3)$  we have

$$(16) \quad E_\varepsilon(u_\varepsilon) = \int_{\Sigma_1} W\left(\partial_1 \hat{u}_\varepsilon(x, x_3) \mid \partial_2 \hat{u}_\varepsilon(x, x_3) \mid \frac{1}{\varepsilon} \partial_3 \hat{u}_\varepsilon(x, x_3)\right) dx dx_3.$$

Using the coercivity of  $W$ , we deduce that  $\|\partial_3 \hat{u}_\varepsilon\|_{L^p(\Sigma_1; \mathbb{R}^3)} \leq c\varepsilon^p$  for all  $\varepsilon > 0$  and some  $c > 0$ , and so  $\|\hat{u}_\varepsilon - v_\varepsilon\|_{L^p(\Sigma_1; \mathbb{R}^3)} \leq c'\varepsilon^p$  by Poincaré-Wirtinger's inequality, where  $c' > 0$  is a constant which does not depend on  $\varepsilon$ . It follows that  $\hat{u}_\varepsilon \rightarrow v$  in  $L^p(\Sigma_1; \mathbb{R}^3)$ . For  $x_3 \in ]-\frac{1}{2}, \frac{1}{2}[$ , let  $w_\varepsilon^{x_3} \in W^{1,p}(\Sigma; \mathbb{R}^3)$  given by  $w_\varepsilon^{x_3}(x) := \hat{u}_\varepsilon(x, x_3)$ .



Then (up to a subsequence)  $w_\varepsilon^{x_3} \rightarrow v$  in  $L^p(\Sigma; \mathbb{R}^3)$  for a.e.  $x_3 \in ]-\frac{1}{2}, \frac{1}{2}[$ . Taking (15) and (16) into account and using Fatou's lemma, we obtain

$$\liminf_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon(v_\varepsilon) \geq \int_{-\frac{1}{2}}^{\frac{1}{2}} \left( \liminf_{\varepsilon \rightarrow 0} \int_\Sigma W_0(\nabla w_\varepsilon^{x_3}(x)) dx \right) dx_3,$$

and so  $\liminf_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon(v_\varepsilon) \geq \mathcal{I}(v)$ , and (14) follows by using Theorem 2.6.  $\square$

**4.2. Proof of (b).** As  $\Gamma$ -lim sup  $\varepsilon \rightarrow 0$   $\mathcal{E}_\varepsilon$  is lower semicontinuous with respect to the strong topology of  $L^p(\Sigma; \mathbb{R}^3)$  (see [11, Proposition 6.8 p. 57]), it is sufficient to prove that for every  $v \in C_*^1(\overline{\Sigma}; \mathbb{R}^3)$ ,

$$(17) \quad \limsup_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon(v) \leq \mathcal{E}(v).$$

Given  $v \in C_*^1(\overline{\Sigma}; \mathbb{R}^3)$ , fix any  $j \geq 1$ , and any  $n \geq 1$ . Using Theorem 3.4 we obtain the existence of  $\phi \in C(\overline{\Sigma}; \Lambda_v^j)$  such that

$$(18) \quad \int_\Sigma W(\nabla v(x) \mid \phi(x)) dx \leq \mathcal{E}(v) + \frac{1}{n}.$$

By Stone-Weierstrass's approximation theorem, there exists  $\{\phi_k\}_{k \geq 1} \subset C^\infty(\overline{\Sigma}; \mathbb{R}^3)$  such that

$$(19) \quad \phi_k \rightarrow \phi \text{ uniformly as } k \rightarrow +\infty.$$

We claim that:

$$(c_1) \quad \det(\nabla v(x) \mid \phi_k(x)) \geq \frac{1}{2j} \text{ for all } x \in \overline{\Sigma}, \text{ all } k \geq k_v \text{ and some } k_v \geq 1;$$

$$(c_2) \quad \lim_{k \rightarrow +\infty} \int_\Sigma W(\nabla v(x) \mid \phi_k(x)) dx = \int_\Sigma W(\nabla v(x) \mid \phi(x)) dx.$$

Indeed, setting  $\mu_v := \sup_{x \in \overline{\Sigma}} |\partial_1 v(x) \wedge \partial_2 v(x)|$  ( $\mu_v > 0$ ) and using (19), we deduce that there exists  $k_v \geq 1$  such that for every  $k \geq k_v$ ,

$$(20) \quad \sup_{x \in \overline{\Sigma}} |\phi_k(x) - \phi(x)| < \frac{1}{2j\mu_v}.$$

Let  $x \in \overline{\Sigma}$ , and let  $k \geq k_v$ . As  $\phi \in C(\overline{\Sigma}; \Lambda_v^j)$  we have

$$(21) \quad \det(\nabla v(x) \mid \phi_k(x)) \geq \frac{1}{j} - \det(\nabla v(x) \mid \phi_k(x) - \phi(x)).$$

Noticing that  $\det(\nabla v(x) \mid \phi_k(x) - \phi(x)) \leq |\partial_1 v(x) \wedge \partial_2 v(x)| |\phi_k(x) - \phi(x)|$ , from (20) and (21) we deduce that  $\det(\nabla v(x) \mid \phi_k(x)) \geq \frac{1}{2j}$ , and (c<sub>1</sub>) is proved. Combining (c<sub>1</sub>) with (2) we see that  $\sup_{k \geq k_v} W(\nabla v(\cdot) \mid \phi_k(\cdot)) \in L^1(\Sigma)$ . As  $W$  is continuous we have  $\lim_{k \rightarrow +\infty} W(\nabla v(x) \mid \phi_k(x)) = W(\nabla v(x) \mid \phi(x))$  for all  $x \in V$ , and (c<sub>2</sub>) follows by using Lebesgue's dominated convergence theorem, which completes the claim.

Fix any  $k \geq k_v$  and define  $\theta : ]-\frac{1}{2}, \frac{1}{2}[ \rightarrow \mathbb{R}$  by  $\theta(x_3) := \inf_{x \in \overline{\Sigma}} \det(\nabla v(x) + x_3 \nabla \phi_k(x) \mid \phi_k(x))$ . Clearly  $\theta$  is continuous. By (c<sub>1</sub>) we have  $\theta(0) \geq \frac{1}{2j}$ , and so there exists  $\eta_v \in ]0, \frac{1}{2}[$  such that  $\theta(x_3) \geq \frac{1}{4j}$  for all  $x_3 \in ]-\eta_v, \eta_v[$ . Let  $u_k : \Sigma_1 \rightarrow \mathbb{R}$  be given by  $u_k(x, x_3) := v(x) + x_3 \phi_k(x)$ . From the above it follows that

$$(c_3) \quad \det \nabla u_k(x, \varepsilon x_3) \geq \frac{1}{4j} \text{ for all } \varepsilon \in ]0, \eta_v[ \text{ and all } (x, x_3) \in \overline{\Sigma} \times ]-\frac{1}{2}, \frac{1}{2}[.$$

As in the proof of (c<sub>1</sub>), from (c<sub>3</sub>) together with (2) and the continuity of  $W$ , we obtain

$$(22) \quad \lim_{\varepsilon \rightarrow 0} E_\varepsilon(u_k) = \lim_{\varepsilon \rightarrow 0} \int_{\Sigma_1} W(\nabla u_k(x, \varepsilon x_3)) dx dx_3 = \int_{\Sigma} W(\nabla v(x) \mid \phi_k(x)) dx.$$

For every  $\varepsilon > 0$  and every  $k \geq k_v$ , since  $\pi_\varepsilon(u_k) = v$  we have  $\mathcal{E}_\varepsilon(v) \leq E_\varepsilon(u_k)$ . Using (22), (c<sub>2</sub>) and (18), we deduce that

$$\limsup_{\varepsilon \rightarrow 0} \mathcal{E}_\varepsilon(v) \leq \mathcal{E}(v) + \frac{1}{n},$$

and (17) follows by letting  $n \rightarrow +\infty$ .  $\square$

## 5. A SIMPLIFIED FORMULA FOR $\bar{\mathcal{E}}$

In this section, we prove of Theorem 2.6. It is based upon two approximation theorems by Ben Belgacem-Bennequin (see Sect. A.1) and Gromov-Eliasberg (see Sect. A.2).

Recall the definition of rank one convexity and rank one convex envelope:

**Definition 5.1.** Let  $f : \mathbb{M}^{3 \times 2} \rightarrow [0, +\infty]$  be a Borel measurable function.

- (i) We say that  $f$  is rank one convex if for every  $\alpha \in ]0, 1[$  and every  $\xi, \xi' \in \mathbb{M}^{3 \times 2}$  with  $\text{rank}(\xi - \xi') = 1$ ,

$$f(\alpha\xi + (1 - \alpha)\xi') \leq \alpha f(\xi) + (1 - \alpha)f(\xi').$$

- (ii) By the rank one convex envelope of  $f$ , that we denote by  $\mathcal{R}f$ , we mean the greatest rank one convex function which less than or equal to  $f$ .

In [7, Proposition 7 p. 32 and Lemma 8 p. 34] (see also [9, Sect. 5.1], [19, Proposition 3.4.4 p. 112] and [20, Lemma 6.5]) Ben Belgacem proved the following lemma that we will use in the proof of Theorem 2.6. (As  $W_0$  is coercive, it is easy to see that  $\mathcal{R}W_0$  is coercive.)

**Lemma 5.2.** *If (6) holds then:*

- (i)  $\mathcal{R}W_0(\xi) \leq c(1 + |\xi|^p)$  for all  $\xi \in \mathbb{M}^{3 \times 2}$  and some  $c > 0$ ;  
(ii)  $\mathcal{R}W_0$  is continuous.

Define  $I : W^{1,p}(\Sigma; \mathbb{R}^3) \rightarrow [0, +\infty]$  by

$$I(v) := \inf \left\{ \liminf_{n \rightarrow +\infty} \int_{\Sigma} W_0(\nabla v_n(x)) dx : \text{Aff}_{\text{li}}(\Sigma; \mathbb{R}^3) \ni v_n \rightarrow v \text{ in } L^p(\Sigma; \mathbb{R}^3) \right\}$$

with  $\text{Aff}_{\text{li}}(\Sigma; \mathbb{R}^3) := \{v \in \text{Aff}(\Sigma; \mathbb{R}^3) : v \text{ is locally injective}\}$  ( $\text{Aff}(\Sigma; \mathbb{R}^3)$  is defined in Sect. 2.3). To prove Theorem 2.6 we will use Proposition 5.3.

**Proposition 5.3.**  *$I = J$  with  $J : W^{1,p}(\Sigma; \mathbb{R}^3) \rightarrow [0, +\infty]$  given by*

$$J(v) := \inf \left\{ \liminf_{n \rightarrow +\infty} \int_{\Sigma} \mathcal{R}W_0(\nabla v_n(x)) dx : \text{Aff}_{\text{li}}(\Sigma; \mathbb{R}^3) \ni v_n \rightarrow v \text{ in } L^p(\Sigma; \mathbb{R}^3) \right\}.$$

To prove Proposition 5.3 we need Lemma 5.4 whose proof is contained in the thesis of Ben Belgacem [7]. Since it is difficult to lay hands on this thesis (which is written in French), we give the proof of Lemma 5.4 in appendix B.

**Lemma 5.4.**  *$I(v) \leq \int_{\Sigma} \mathcal{R}W_0(\nabla v(x)) dx$  for all  $v \in \text{Aff}_{\text{li}}(\Sigma; \mathbb{R}^3)$ .*

*Proof of Proposition 5.3.* Clearly  $J \leq I$ . We are thus reduced to prove that

$$(23) \quad I \leq J.$$

Fix any  $v \in W^{1,p}(\Sigma; \mathbb{R}^3)$  and any sequence  $v_n \rightarrow v$  in  $L^p(\Sigma; \mathbb{R}^3)$  with  $v_n \in \text{Aff}_{\text{li}}(\Sigma; \mathbb{R}^3)$ . Using Lemma 5.4 we have  $I(v_n) \leq \int_{\Sigma} \mathcal{R}W_0(\nabla v_n(x)) dx$  for all  $n \geq 1$ . Thus,

$$I(v) \leq \liminf_{n \rightarrow +\infty} I(v_n) \leq \liminf_{n \rightarrow +\infty} \int_{\Sigma} \mathcal{R}W_0(\nabla v_n(x)) dx,$$

and (23) follows.  $\square$

*Proof of Theorem 2.6.* We first prove that

$$(24) \quad \bar{\mathcal{E}} \leq I.$$

As in the proof of Proposition 5.3, it suffices to show that if  $v \in \text{Aff}_{\text{li}}(\Sigma; \mathbb{R}^3)$  then

$$(25) \quad \bar{\mathcal{E}}(v) \leq \int_{\Sigma} W_0(\nabla v(x)) dx.$$

Let  $v \in \text{Aff}_{\text{li}}(\Sigma; \mathbb{R}^3)$ . By Theorem A.1-bis (and Lemma A.2), there exists  $\{v_n\}_{n \geq 1} \subset C_*^1(\bar{\Sigma}; \mathbb{R}^3)$  such that (28) and (29) holds and  $\nabla v_n(x) \rightarrow \nabla v(x)$  a.e. in  $\Sigma$ . As  $W_0$  is continuous (see Lemma 2.4(i)), we have

$$\lim_{n \rightarrow +\infty} W_0(\nabla v_n(x)) = W_0(\nabla v(x)) \quad \text{a.e. in } \Sigma.$$

Using (6) together with (29), we deduce that there exists  $c > 0$  such that for every  $n \geq 1$  and every measurable set  $A \subset \Sigma$ ,

$$\int_A W_0(\nabla v_n(x)) dx \leq c \left( |A| + \int_A |\nabla v_n(x) - \nabla v(x)|^p dx + \int_A |\nabla v(x)|^p dx \right).$$

But  $\nabla v_n \rightarrow \nabla v$  in  $L^p(\Sigma; \mathbb{M}^{3 \times 2})$  by (28), hence  $\{W_0(\nabla v_n(\cdot))\}_{n \geq 1}$  is absolutely uniformly integrable. Using Vitali's theorem, we obtain

$$\lim_{n \rightarrow +\infty} \int_{\Sigma} W_0(\nabla v_n(x)) dx = \int_{\Sigma} W_0(\nabla v(x)) dx,$$

and (25) follows.

We now prove that

$$(26) \quad J \leq \bar{J},$$

with  $\bar{J} : W^{1,p}(\Sigma; \mathbb{R}^3) \rightarrow [0, +\infty]$  given by

$$\bar{J}(v) := \inf \left\{ \liminf_{n \rightarrow +\infty} \int_{\Sigma} \mathcal{R}W_0(\nabla v_n(x)) dx : W^{1,p}(\Sigma; \mathbb{R}^3) \ni v_n \rightarrow v \text{ in } L^p(\Sigma; \mathbb{R}^3) \right\}.$$

It is sufficient to show that

$$(27) \quad J(v) \leq \int_{\Sigma} \mathcal{R}W_0(\nabla v(x)) dx.$$

Let  $v \in W^{1,p}(\Sigma; \mathbb{R}^3)$ . By Corollary A.6, there exists  $\{v_n\}_{n \geq 1} \subset \text{Aff}_{\text{li}}(\Sigma; \mathbb{R}^3)$  such that  $\nabla v_n \rightarrow \nabla v$  in  $L^p(\Sigma; \mathbb{R}^3)$  and  $\nabla v_n(x) \rightarrow \nabla v(x)$  a.e. in  $\Sigma$ . Taking Lemma 5.2 into account, from Vitali's lemma, we see that

$$\lim_{n \rightarrow +\infty} \int_{\Sigma} \mathcal{R}W_0(\nabla v_n(x)) dx = \int_{\Sigma} \mathcal{R}W_0(\nabla v(x)) dx,$$

and (27) follows.

Noticing that  $\mathcal{I} \leq \overline{\mathcal{E}}$  and  $\overline{\mathcal{J}} \leq \mathcal{I}$ , and combining Proposition 5.3 with (24) and (26), we conclude that  $\overline{\mathcal{E}} = \mathcal{I}$ .  $\square$

## APPENDIX A. APPROXIMATION THEOREMS

**A.1. Ben Belgacem-Bennequin's theorem.** Denote by  $\text{Aff}^{ET}(\Sigma; \mathbb{R}^3)$  the space of Ekeland-Temam continuous piecewise affine functions from  $\Sigma$  to  $\mathbb{R}^3$ , i.e.,  $u \in \text{Aff}^{ET}(\Sigma; \mathbb{R}^3)$  if and only if  $v$  is continuous and there exists a finite family  $(V_i)_{i \in I}$  of open disjoint subsets of  $\Sigma$  such that  $|\Sigma \setminus \cup_{i \in I} V_i| = 0$  and for every  $i \in I$ , the restriction of  $v$  to  $V_i$  is affine. Note that from Ekeland-Temam [12], we know that  $\text{Aff}^{ET}(\Sigma; \mathbb{R}^3)$  is strongly dense in  $W^{1,p}(\Sigma; \mathbb{R}^3)$ . Set

$$\text{Aff}_{\text{li}}^{ET}(\Sigma; \mathbb{R}^3) := \left\{ v \in \text{Aff}^{ET}(\Sigma; \mathbb{R}^3) : v \text{ is locally injective} \right\}.$$

In [7, Lemma 8 p. 114] (see also [19, Proposition C.0.4 p. 127] and [20, Lemma 1.3]) Ben Belgacem and Bennequin proved the following result.

**Theorem A.1.** *For every  $v \in \text{Aff}_{\text{li}}^{ET}(\Sigma; \mathbb{R}^3)$ , there exists  $\{v_n\}_{n \geq 1} \subset C_*^1(\overline{\Sigma}; \mathbb{R}^3)$  such that:*

$$(28) \quad v_n \rightarrow v \text{ in } W^{1,p}(\Sigma; \mathbb{R}^3);$$

$$(29) \quad |\partial_1 v_n(x) \wedge \partial_2 v_n(x)| \geq \delta \text{ for all } x \in \overline{\Sigma}, \text{ all } n \geq 1 \text{ and some } \delta > 0.$$

Denote by  $\text{Aff}^V(\Sigma; \mathbb{R}^3)$  the space of Vitali continuous piecewise affine functions from  $\Sigma$  to  $\mathbb{R}^3$  (introduced by Ben Belgacem in [7, 9]), i.e.,  $v \in \text{Aff}^V(\Sigma; \mathbb{R}^3)$  if and only if  $v$  is continuous and there exists a finite or countable family  $(O_i)_{i \in I}$  of disjoint open subsets of  $\Sigma$  such that  $|\partial O_i| = 0$  for all  $i \in I$ ,  $|\Sigma \setminus \cup_{i \in I} O_i| = 0$ , and  $v(x) = \xi_i \cdot x + a_i$  if  $x \in O_i$ , where  $a_i \in \mathbb{R}^3$ ,  $\xi_i \in \mathbb{M}^{3 \times 2}$  and  $\text{Card}\{\xi_i : i \in I\}$  is finite. In [19, Lemma 3.1.5 p. 99] Trabelsi remarked that Theorem A.1 can be generalized replacing the space  $\text{Aff}_{\text{li}}^{ET}(\Sigma; \mathbb{R}^3)$  by

$$\text{Aff}_{\text{li}}^V(\Sigma; \mathbb{R}^3) := \left\{ v \in \text{Aff}^V(\Sigma; \mathbb{R}^3) : v \text{ is locally injective} \right\}.$$

**Theorem A.1-bis.** *For every  $v \in \text{Aff}_{\text{li}}^V(\Sigma; \mathbb{R}^3)$ , there exists  $\{v_n\}_{n \geq 1} \subset C_*^1(\overline{\Sigma}; \mathbb{R}^3)$  satisfying (28) and (29).*

Here we consider the space  $\text{Aff}(\Sigma; \mathbb{R}^3)$  defined in Sect. 2.3. It is clear that  $\text{Aff}^{ET}(\Sigma; \mathbb{R}^3) \subset \text{Aff}(\Sigma; \mathbb{R}^3)$ , and so  $\text{Aff}(\Sigma; \mathbb{R}^3)$  is strongly dense in  $W^{1,p}(\Sigma; \mathbb{R}^3)$ . Moreover, we have

**Lemma A.2.**  $\text{Aff}^V(\Sigma; \mathbb{R}^3) = \text{Aff}(\Sigma; \mathbb{R}^3)$ .

*Proof.* Setting  $D_i := \{x \in \cup_{i \in I} O_i : \nabla v(x) = \xi_i\}$  with  $v \in \text{Aff}^V(\Sigma; \mathbb{R}^3)$ , we see that  $\text{Card}\{D_i : i \in I\}$  is finite. Thus  $\text{Aff}^V(\Sigma; \mathbb{R}^3) \subset \text{Aff}(\Sigma; \mathbb{R}^3)$ . Given  $v \in \text{Aff}(\Sigma; \mathbb{R}^3)$ , let  $(O_j)_{j \in J_i}$  be the connected components of  $D_i$  with  $i \in I$  (where  $I$  is finite). Since  $D_i$  is open,  $O_j$  is open for all  $j \in J_i$ , hence  $J_i$  is finite or countable because  $\mathbb{Q}^2$  is dense in  $\mathbb{R}^2$ . Moreover, for each  $j \in J_i$ , the restriction of  $v$  to  $O_j$  is affine. Thus  $\text{Aff}(\Sigma; \mathbb{R}^3) \subset \text{Aff}^V(\Sigma; \mathbb{R}^3)$ .  $\square$

**A.2. Gromov-Eliashberg's theorem.** In [14, Theorem 1.3.4B] (see also [15, Theorem B'<sub>1</sub> p. 20]) Gromov and Eliashberg proved the following result.

**Theorem A.3.** *Let  $1 \leq N < m$  be two integers and let  $M$  be a compact  $N$ -dimensional manifold which can be immersed in  $\mathbb{R}^m$ . Then, for each  $C^1$ -differentiable function  $v$  from  $M$  to  $\mathbb{R}^m$  there exists a sequence  $\{v_n\}_n$  of  $C^1$ -immersions from  $M$  to  $\mathbb{R}^m$  such that  $v_n \rightarrow v$  in  $W^{1,p}(M; \mathbb{R}^m)$ .*

In our context, we have

**Theorem A.4.** *For every  $v \in C^1(\overline{\Sigma}; \mathbb{R}^3)$  there exists  $\{v_n\}_{n \geq 1} \subset C_*^1(\overline{\Sigma}; \mathbb{R}^3)$  such that  $v_n \rightarrow v$  in  $W^{1,p}(\Sigma; \mathbb{R}^3)$ .*

Moreover, from [19, Proposition 3.1.7 p. 100], we have

**Proposition A.5.** *For every  $v \in C_*^1(\overline{\Sigma}; \mathbb{R}^3)$  there exists  $\{v_n\}_{n \geq 1} \subset \text{Aff}_{\text{li}}^{ET}(\Sigma; \mathbb{R}^3)$  such that  $v_n \rightarrow v$  in  $W^{1,p}(\Sigma; \mathbb{R}^3)$ .*

Thus, as a consequence of Theorem A.4 and Proposition A.5, we obtain

**Corollary A.6.**  *$\text{Aff}_{\text{li}}^{ET}(\Sigma; \mathbb{R}^3)$  is strongly dense in  $W^{1,p}(\Sigma; \mathbb{R}^3)$ .*

#### APPENDIX B. BEN BELGACEM'S LEMMA

In this appendix we prove Ben Belgacem's lemma, i.e., Lemma 5.4.

**B.1. Preliminaries.** Define the sequence  $\{\mathcal{R}_i W_0\}_{i \geq 0}$  by  $\mathcal{R}_0 W_0 = W_0$  and for every  $i \geq 1$  and every  $\xi \in \mathbb{M}^{3 \times 2}$ ,

$$\mathcal{R}_{i+1} W_0(\xi) := \inf_{\substack{a \in \mathbb{R}^2 \\ b \in \mathbb{R}^3 \\ t \in [0,1]}} \left\{ (1-t)\mathcal{R}_i W_0(\xi - ta \otimes b) + t\mathcal{R}_i W_0(\xi + (1-t)a \otimes b) \right\}.$$

Recall that  $W_0$  is coercive and continuous (see Lemma 2.4(i)). The following lemma is due to Kohn and Strang [16].

**Lemma B.1.**  *$\mathcal{R}_{i+1} W_0 \leq \mathcal{R}_i W_0$  for all  $i \geq 0$  and  $\mathcal{R} W_0 = \inf_{i \geq 0} \mathcal{R}_i W_0$ .*

Fix any  $i \geq 0$  and any  $v \in \text{Aff}_{\text{li}}(\Sigma; \mathbb{R}^3) := \{v \in \text{Aff}(\Sigma; \mathbb{R}^3) : v \text{ is locally injective}\}$  (with  $\text{Aff}(\Sigma; \mathbb{R}^3)$  defined in Sect. 2.3). By definition, there exists a finite family  $(V_j)_{j \in J}$  of open disjoint subsets of  $\Sigma$  such that  $|\partial V_j| = 0$  for all  $j \in J$ ,  $|\Sigma \setminus \cup_{j \in J} V_j| = 0$  and, for every  $j \in J$ ,  $\nabla v(x) = \xi_j$  in  $V_j$  with  $\xi_j \in \mathbb{M}^{3 \times 2}$ . (As  $v$  is locally injective we have  $\text{rank}(\xi_j) = 2$  for all  $j \in J$ .) Fix any  $j \in J$ . For a proof of Lemmas B.2 and B.3 we refer to [19, Proposition 3.1.2 p. 96].

**Lemma B.2.**  *$\mathcal{R}_i W_0$  is continuous.*

**Lemma B.3.** *There exist  $a \in \mathbb{R}^2$ ,  $b \in \mathbb{R}^3$  and  $t \in [0, 1]$  such that*

$$\mathcal{R}_{i+1} W_0(\xi_j) = (1-t)\mathcal{R}_i W_0(\xi_j - ta \otimes b) + t\mathcal{R}_i W_0(\xi_j + (1-t)a \otimes b).$$

Without loss of generality we can assume that  $a = (1, 0)$ . For each  $n \geq 3$  and each  $k \in \{0, \dots, n-1\}$ , consider  $A_{k,n}^-, A_{k,n}^+, B_{k,n}^-, B_{k,n}^+, C_{k,n}^-, C_{k,n}^+ \subset Y$  given by:

$$\begin{aligned} A_{k,n}^- &:= \left\{ (x_1, x_2) \in Y : \frac{k}{n} \leq x_1 \leq \frac{k}{n} + \frac{1-t}{n} \text{ and } \frac{1}{n} \leq x_2 \leq 1 - \frac{1}{n} \right\}; \\ A_{k,n}^+ &:= \left\{ (x_1, x_2) \in Y : \frac{k}{n} + \frac{1-t}{n} \leq x_1 \leq \frac{k+1}{n} \text{ and } \frac{1}{n} \leq x_2 \leq 1 - \frac{1}{n} \right\}; \\ B_{k,n} &:= \left\{ (x_1, x_2) \in Y : \frac{k}{n} \leq x_1 \leq \frac{k+1}{n} \text{ and } 0 \leq x_2 \leq -x_1 + \frac{k+1}{n} \right\}; \end{aligned}$$

$$\begin{aligned}
B_{k,n}^- &:= \{(x_1, x_2) \in Y : -x_2 + \frac{k+1}{n} \leq x_1 \leq -tx_2 + \frac{k+1}{n} \text{ and } 0 \leq x_2 \leq \frac{1}{n}\}; \\
B_{k,n}^+ &:= \{(x_1, x_2) \in Y : -tx_2 + \frac{k+1}{n} \leq x_1 \leq \frac{k+1}{n} \text{ and } 0 \leq x_2 \leq \frac{1}{n}\}; \\
C_{k,n} &:= \{(x_1, x_2) \in Y : \frac{k}{n} \leq x_1 \leq \frac{k+1}{n} \text{ and } x_1 + 1 - \frac{k+1}{n} \leq x_2 \leq 1\}; \\
C_{k,n}^- &:= \{(x_1, x_2) \in Y : x_2 - 1 + \frac{k+1}{n} \leq x_1 \leq t(x_2 - 1) + \frac{k+1}{n} \text{ and } 0 \leq x_2 \leq \frac{1}{n}\}; \\
C_{k,n}^+ &:= \{(x_1, x_2) \in Y : t(x_2 - 1) + \frac{k+1}{n} \leq x_1 \leq \frac{k+1}{n} \text{ and } 0 \leq x_2 \leq \frac{1}{n}\},
\end{aligned}$$

and define  $\{\sigma_n\}_{n \geq 1} \subset \text{Aff}_0(Y; \mathbb{R})$  by

$$\sigma_n(x_1, x_2) := \begin{cases} -t(x_1 - \frac{k}{n}) & \text{if } (x_1, x_2) \in A_{k,n}^- \\ (1-t)(x_1 - \frac{k+1}{n}) & \text{if } (x_1, x_2) \in A_{k,n}^+ \cup B_{k,n}^+ \cup C_{k,n}^+ \\ -t(x_1 + x_2 - \frac{k+1}{n}) & \text{if } (x_1, x_2) \in B_{k,n}^- \\ -t(x_1 - x_2 + 1 - \frac{k+1}{n}) & \text{if } (x_1, x_2) \in C_{k,n}^- \\ 0 & \text{if } (x_1, x_2) \in B_{k,n} \cup C_{k,n} \end{cases}$$

(see Figure B.1).

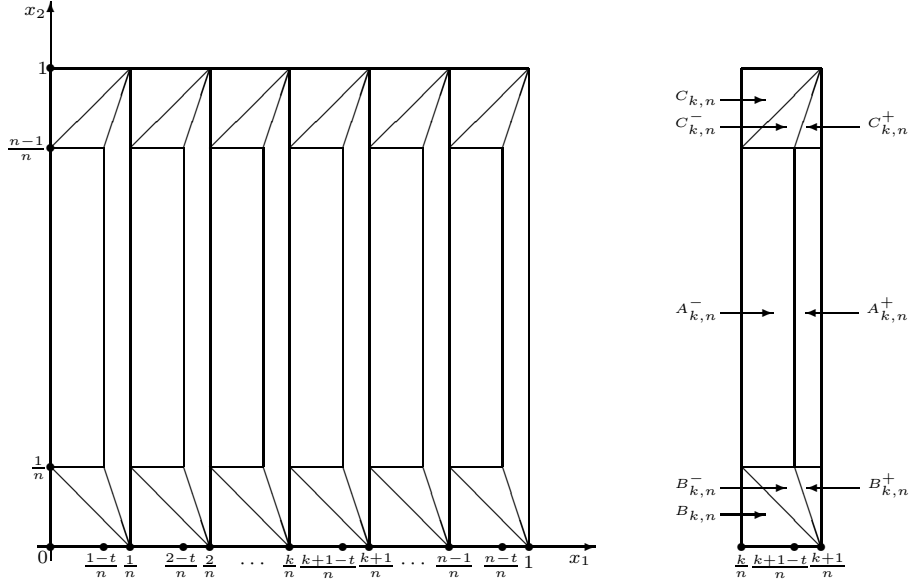


Figure B.1. The function  $\sigma_n$  and the sets  $A_{k,n}^-, A_{k,n}^+, B_{k,n}^-, B_{k,n}^+, C_{k,n}^-, C_{k,n}^+, B_{k,n}, C_{k,n}$ .

Set

$$b_\ell := \begin{cases} b & \text{if } b \notin \text{Im}\xi_j \\ b + \frac{1}{\ell}\nu & \text{if } b \in \text{Im}\xi_j \end{cases}$$

(with  $\text{Im}\xi_j := \{\xi_j \cdot x : x \in \mathbb{R}^2\}$ ) where  $\ell \geq 1$  and  $\nu \in \mathbb{R}^3$  is a normal vector to  $\text{Im}\xi_j$ .

**Lemma B.4.** Define  $\{\theta_{n,\ell}\}_{n,\ell \geq 1} \subset \text{Aff}_0(Y; \mathbb{R}^3)$  by

$$\theta_{n,\ell}(x) := \sigma_n(x)b_\ell.$$

Then:

- (i) for every  $\ell \geq 1$ ,  $\theta_{n,\ell} \rightarrow 0$  in  $L^p(Y; \mathbb{R}^3)$ ;
- (ii)  $\lim_{\ell \rightarrow +\infty} \lim_{n \rightarrow +\infty} \int_Y \mathcal{R}_i W_0(\xi_j + \nabla \theta_{n,\ell}(x)) dx = \mathcal{R}_{i+1} W_0(\xi_j)$ .

*Proof.* (i) It suffices to prove that  $\sigma_n \rightarrow 0$  in  $L^p(Y; \mathbb{R})$ . For every  $k \in \{0, \dots, n-1\}$ , it is clear that  $|\sigma_n(x)|^p \leq \frac{t^p(1-t)^p}{n^p}$  for all  $x \in ]\frac{k}{n}, \frac{k+1}{n}[ \times ]0, 1[$ , and so

$$\int_{]\frac{k}{n}, \frac{k+1}{n}[ \times ]0, 1[} |\sigma_n(x)|^p dx \leq \frac{t^p(1-t)^p}{n^{p+1}}.$$

As

$$\int_Y |\sigma_n(x)|^p dx = \sum_{k=0}^{n-1} \int_{]\frac{k}{n}, \frac{k+1}{n}[ \times ]0, 1[} |\sigma_n(x)|^p dx$$

it follows that

$$\int_Y |\sigma_n(x)|^p dx \leq \frac{t^p(1-t)^p}{n^p},$$

which gives the desired conclusion.

(ii) Recalling that  $a = (1, 0)$  we see that

$$\xi_j + \nabla \theta_{n,\ell}(x) := \begin{cases} \xi_j - ta \otimes b_\ell & \text{if } x \in \text{int}(A_{k,n}^-) \\ \xi_j + (1-t)a \otimes b_\ell & \text{if } x \in \text{int}(A_{k,n}^+ \cup B_{k,n}^+ \cup C_{k,n}^+) \\ \xi_j - t(a + a^\perp) \otimes b_\ell & \text{if } x \in \text{int}(B_{k,n}^-) \\ \xi_j - t(a - a^\perp) \otimes b_\ell & \text{if } x \in \text{int}(C_{k,n}^-) \\ \xi_j & \text{if } x \in \text{int}(B_{k,n}) \cup \text{int}(C_{k,n}) \end{cases}$$

with  $a^\perp = (0, 1)$  (and  $\text{int}(E)$  denotes the interior of the set  $E$ ). Moreover, we have:

$$\begin{aligned} \int_{\cup_{k=0}^{n-1} A_{k,n}^-} \mathcal{R}_i W_0(\xi_j - ta \otimes b_\ell) dx &= (1-t)(1 - \frac{2}{n}) \mathcal{R}_i W_0(\xi_j - ta \otimes b_\ell); \\ \int_{\cup_{k=0}^{n-1} A_{k,n}^+} \mathcal{R}_i W_0(\xi_j + (1-t)a \otimes b_\ell) dx &= t(1 - \frac{2}{n}) \mathcal{R}_i W_0(\xi_j + (1-t)a \otimes b_\ell); \\ \int_{\cup_{k=0}^{n-1} (B_{k,n}^+ \cup C_{k,n}^+)} \mathcal{R}_i W_0(\xi_j + (1-t)a \otimes b_\ell) dx &= \frac{t}{n} \mathcal{R}_i W_0(\xi_j + (1-t)a \otimes b_\ell); \\ \int_{\cup_{k=0}^{n-1} B_{k,n}^-} \mathcal{R}_i W_0(\xi_j - t(a + a^\perp) \otimes b_\ell) dx &= \frac{1-t}{2n} \mathcal{R}_i W_0(\xi_j - t(a + a^\perp) \otimes b_\ell); \\ \int_{\cup_{k=0}^{n-1} C_{k,n}^-} \mathcal{R}_i W_0(\xi_j - t(a - a^\perp) \otimes b_\ell) dx &= \frac{1-t}{2n} \mathcal{R}_i W_0(\xi_j - t(a - a^\perp) \otimes b_\ell); \\ \int_{\cup_{k=0}^{n-1} (B_{k,n} \cup C_{k,n})} \mathcal{R}_i W_0(\xi_j) dx &= \frac{1}{n} \mathcal{R}_i W_0(\xi_j). \end{aligned}$$

Hence

$$\begin{aligned} \int_Y \mathcal{R}_i W_0(\xi_j + \nabla \theta_{n,\ell}(x)) dx &= \left(1 - \frac{2}{n}\right) \left[ (1-t) \mathcal{R}_i W_0(\xi_j - ta \otimes b_\ell) + t \mathcal{R}_i W_0(\xi_j \right. \\ &\quad \left. + (1-t)a \otimes b_\ell) \right] + \frac{1}{n} \left[ t \mathcal{R}_i W_0(\xi_j + (1-t)a \otimes b_\ell) \right. \\ &\quad \left. + \frac{1-t}{2} (\mathcal{R}_i W_0(\xi_j - t(a + a^\perp) \otimes b_\ell) + \mathcal{R}_i W_0(\xi_j - \right. \\ &\quad \left. t(a - a^\perp) \otimes b_\ell)) + \mathcal{R}_i W_0(\xi_j) \right] \end{aligned}$$

for all  $n, \ell \geq 1$ . It follows that for every  $\ell \geq 1$ ,

$$\begin{aligned} \lim_{n \rightarrow +\infty} \int_Y \mathcal{R}_i W_0(\xi_j + \nabla \theta_{n,\ell}(x)) dx &= (1-t) \mathcal{R}_i W_0(\xi_j - ta \otimes b_\ell) \\ &\quad + t \mathcal{R}_i W_0(\xi_j + (1-t)a \otimes b_\ell). \end{aligned}$$

Taking Lemma B.2 into account and noticing that  $b_\ell \rightarrow b$ , we deduce that

$$\begin{aligned} \lim_{\ell \rightarrow +\infty} \lim_{n \rightarrow +\infty} \int_Y \mathcal{R}_i W_0(\xi_j + \nabla \theta_{n,\ell}(x)) dx &= (1-t) \mathcal{R}_i W_0(\xi_j - ta \otimes b) \\ &\quad + t \mathcal{R}_i W_0(\xi_j + (1-t)a \otimes b), \end{aligned}$$

and (ii) follows by using Lemma B.3.  $\square$

Consider  $V_q^j \subset V_j$  given by  $V_q^j := \{x \in V_j : \text{dist}(x, \partial V_j) > \frac{1}{q}\}$  with  $q \geq 1$  large enough. By Vitali's covering theorem, there exists a finite or countable family  $(r_m + \rho_m Y)_{m \in M}$  of disjoint subsets of  $V_q^j$ , with  $r_m \in \mathbb{R}^2$  and  $\rho_m \in ]0, 1[$ , such that  $|V_q^j \setminus \cup_{m \in M} (r_m + \rho_m Y)| = 0$  (and so  $\sum_{m \in M} \rho_m^2 = |V_q^j|$ ). Let  $\{\phi_{n,\ell,q}\}_{n,\ell,q \geq 1} \subset \text{Aff}_0(V_j; \mathbb{R}^3)$  be given by

$$\phi_{n,\ell,q}(x) := \begin{cases} \rho_m \theta_{n,\ell} \left( \frac{x - r_m}{\rho_m} \right) & \text{if } x \in r_m + \rho_m Y \subset V_q^j \\ 0 & \text{if } x \in V_j \setminus V_q^j. \end{cases}$$

**Lemma B.5.** Define  $\{\Phi_{n,\ell,q}^j\}_{n,\ell,q \geq 1} \subset \text{Aff}(V_j; \mathbb{R}^3)$  by

$$(30) \quad \Phi_{n,\ell,q}^j(x) := v(x) + \phi_{n,\ell,q}(x).$$

Then:

- (i) for every  $n, \ell, q \geq 1$ ,  $\Phi_{n,\ell,q}^j$  is locally injective;
- (ii) for every  $\ell, q \geq 1$ ,  $\Phi_{n,\ell,q}^j \rightarrow v$  in  $L^p(V_j; \mathbb{R}^3)$ ;
- (iii)  $\lim_{q \rightarrow +\infty} \lim_{\ell \rightarrow +\infty} \lim_{n \rightarrow +\infty} \int_{V_j} \mathcal{R}_i W_0(\nabla \Phi_{n,\ell,q}^j(x)) dx = |V_j| \mathcal{R}_{i+1} W_0(\xi_j)$ .

*Proof.* (i) Let  $x \in V_j$  and let  $W \subset V_j$  be the connected component of  $V_j$  such that  $x \in W$  (as  $V_j$  is open, so is  $W$ ). Since  $\nabla v = \xi_j$  in  $W$ , there exists  $c \in \mathbb{R}^3$  such that  $v(x') = \xi_j \cdot x' + c$  for all  $x' \in W$ . We claim that  $\Phi_{n,\ell,q}^j|_W$  is injective. Indeed, let  $x' \in W$  be such that  $\Phi_{n,\ell,q}^j(x) = \Phi_{n,\ell,q}^j(x')$ . One of the three possibilities holds:

- (a)  $\Phi_{n,\ell,q}^j(x) = \xi_j \cdot x + c + \rho_m \sigma_n \left( \frac{x - r_m}{\rho_m} \right) b_\ell$  and  $\Phi_{n,\ell,q}^j(x') = \xi_j \cdot x' + c + \rho_{m'} \sigma_n \left( \frac{x' - r_{m'}}{\rho_{m'}} \right) b_\ell$ ;
- (b)  $\Phi_{n,\ell,q}^j(x) = \xi_j \cdot x + c + \rho_m \sigma_n \left( \frac{x - r_m}{\rho_m} \right) b_\ell$  and  $\Phi_{n,\ell,q}^j(x') = \xi_j \cdot x' + c$ ;
- (c)  $\Phi_{n,\ell,q}^j(x) = \xi_j \cdot x + c$  and  $\Phi_{n,\ell,q}^j(x') = \xi_j \cdot x' + c$ .

Setting  $\alpha := \rho_m \sigma_n \left( \frac{x - r_m}{\rho_m} \right) - \rho_{m'} \sigma_n \left( \frac{x' - r_{m'}}{\rho_{m'}} \right)$  and  $\beta := \rho_m \sigma_n \left( \frac{x - r_m}{\rho_m} \right)$  we have:

$$\begin{cases} \xi_j(x' - x) = 0 & \text{if } \alpha = 0 \\ b_\ell = \frac{1}{\alpha} \xi_j(x' - x) & \text{if } \alpha \neq 0 \end{cases} \quad \text{when (a) is satisfied;} \\ \begin{cases} \xi_j(x' - x) = 0 & \text{if } \beta = 0 \\ b_\ell = \frac{1}{\beta} \xi_j(x' - x) & \text{if } \beta \neq 0 \end{cases} \quad \text{when (b) is satisfied;} \\ \xi_j(x' - x) = 0 \quad \text{when (c) is satisfied.}$$

It follows that if  $x \neq x'$  then either  $\text{rank}(\xi_j) < 2$  or  $b_\ell \in \text{Im} \xi_j$  which is impossible. Hence  $x = x'$ , and the claim is proved. Thus  $\Phi_{n,\ell,q}^j$  is locally injective.

- (ii) As  $\rho_m \in ]0, 1[$  for all  $m \in M$  and  $\sum_{m \in M} \rho_m^2 = |V_q^j|$  we have

$$\int_{V_q^j} |\phi_{n,\ell,q}(x)|^p dx \leq |V_q^j| \int_Y |\theta_{n,\ell}(x)|^p dx.$$



Using Lemma B.4(i) we deduce that for every  $\ell, q \geq 1$ ,

$$\lim_{n \rightarrow +\infty} \int_{V_q^j} |\phi_{n,\ell,q}(x)|^p dx = 0,$$

and (ii) follows.

(iii) Recalling that  $\sum_{m \in M} \rho_m^2 = |V_q^j|$  we see that

$$\begin{aligned} \int_{V_j} \mathcal{R}_i W_0(\nabla \Phi_{n,\ell,q}^j(x)) dx &= \int_{V_j} \mathcal{R}_i W_0(\xi_j + \nabla \phi_{n,\ell,q}(x)) dx \\ &= \int_{V_q^j} \mathcal{R}_i W_0(\xi_j + \nabla \phi_{n,\ell,q}(x)) dx + |V_j \setminus V_q^j| \mathcal{R}_i W_0(\xi_j) \\ &= |V_q^j| \int_Y \mathcal{R}_i W_0(\xi_j + \nabla \theta_{n,\ell}(x)) dx + |V_j \setminus V_q^j| \mathcal{R}_i W_0(\xi_j). \end{aligned}$$

Using Lemma B.4(ii) we deduce that for every  $q \geq 1$ ,

$$\lim_{\ell \rightarrow +\infty} \lim_{n \rightarrow +\infty} \int_{V_j} \mathcal{R}_i W_0(\nabla \Phi_{n,\ell,q}^j(x)) dx = |V_q^j| \mathcal{R}_{i+1} W_0(\xi_j) + |V_j \setminus V_q^j| \mathcal{R}_i W_0(\xi_j),$$

and (iii) follows by noticing that  $|V_q^j| \rightarrow |V_j|$  and  $|V_j \setminus V_q^j| \rightarrow 0$ .  $\square$

**B.2. Proof of Lemma 5.4.** According to Lemma B.1, it is sufficient to show that for every  $i \geq 0$ ,

$$(P_i) \quad I(v) \leq \int_{\Sigma} \mathcal{R}_i W_0(\nabla v(x)) dx \text{ for all } v \in \text{Aff}_{\text{li}}(\Sigma; \mathbb{R}^3).$$

The proof is by induction on  $i$ . As  $R_0 W_0 = W_0$  it is clear that  $(P_0)$  is true. Assume that  $(P_i)$  is true, and prove that  $(P_{i+1})$  is true. Let  $v \in \text{Aff}_{\text{li}}(\Sigma; \mathbb{R}^3)$ . By definition, there exists a finite family  $(V_j)_{j \in J}$  of open disjoint subsets of  $\Sigma$  such that  $|\partial V_j| = 0$  for all  $j \in J$ ,  $|\Sigma \setminus \cup_{j \in J} V_j| = 0$  and, for every  $j \in J$ ,  $\nabla v(x) = \xi_j$  in  $V_j$  with  $\xi_j \in \mathbb{M}^{3 \times 2}$ . Define  $\{\Psi_{n,\ell,q}\}_{n,\ell,q \geq 1} \subset \text{Aff}(\Sigma; \mathbb{R}^3)$  by

$$\Psi_{n,\ell,q}(x) := \Phi_{n,\ell,q}^j(x) \text{ if } x \in V_j$$

with  $\Phi_{n,\ell,q}^j$  given by (30). Taking Lemma B.5(i) into account (and recalling that  $v$  is locally injective), it is easy to see that  $\Psi_{n,\ell,q}$  is locally injective. Using  $(P_i)$  we can assert that

$$I(\Psi_{n,\ell,q}) \leq \int_{\Sigma} \mathcal{R}_i W_0(\nabla \Psi_{n,\ell,q}(x)) dx \text{ for all } n, \ell, q \geq 1.$$

By Lemma B.5(ii) it is clear that for every  $\ell, q \geq 1$ ,  $\Psi_{n,\ell,q} \rightarrow v$  in  $L^p(\Sigma; \mathbb{R}^3)$ . It follows that

$$I(v) \leq \lim_{n \rightarrow +\infty} I(\Psi_{n,\ell,q}) \leq \lim_{n \rightarrow +\infty} \int_{\Sigma} \mathcal{R}_i W_0(\nabla \Psi_{n,\ell,q}(x)) dx \text{ for all } \ell, q \geq 1.$$

Moreover, from Lemma B.5(iii) we see that

$$\lim_{q \rightarrow +\infty} \lim_{\ell \rightarrow +\infty} \lim_{n \rightarrow +\infty} \int_{\Sigma} \mathcal{R}_i W_0(\nabla \Psi_{n,\ell,q}(x)) dx = \int_{\Sigma} \mathcal{R}_{i+1} W_0(\nabla v(x)) dx.$$

Hence

$$I(v) \leq \int_{\Sigma} \mathcal{R}_{i+1} W_0(\nabla v(x)) dx,$$

and the proof is complete.  $\square$

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