

OPTIMAL LOWER EXPONENT FOR THE HIGHER GRADIENT INTEGRABILITY OF SOLUTIONS TO TWO-PHASE ELLIPTIC EQUATIONS IN TWO DIMENSIONS

SILVIO FANZON AND MARIAPIA PALOMBARO

ABSTRACT. We study the higher gradient integrability of distributional solutions u to the equation $\operatorname{div}(\sigma \nabla u) = 0$ in dimension two, in the case when the essential range of σ consists of only two elliptic matrices, i.e., $\sigma \in \{\sigma_1, \sigma_2\}$ a.e. in Ω . In [9], for every pair of elliptic matrices σ_1 and σ_2 , exponents $p_{\sigma_1, \sigma_2} \in (2, +\infty)$ and $q_{\sigma_1, \sigma_2} \in (1, 2)$ have been found so that if $u \in W^{1, q_{\sigma_1, \sigma_2}}(\Omega)$ is solution to the elliptic equation then $\nabla u \in L_{\text{weak}}^{p_{\sigma_1, \sigma_2}}(\Omega)$ and the optimality of the upper exponent p_{σ_1, σ_2} has been proved. In this paper we complement the above result by proving the optimality of the lower exponent q_{σ_1, σ_2} . Precisely, we show that for every arbitrarily small δ , one can find a particular microgeometry, i.e., an arrangement of the sets $\sigma^{-1}(\sigma_1)$ and $\sigma^{-1}(\sigma_2)$, for which there exists a solution u to the corresponding elliptic equation such that $\nabla u \in L^{q_{\sigma_1, \sigma_2} - \delta}$, but $\nabla u \notin L^{q_{\sigma_1, \sigma_2}}$. The existence of such optimal microgeometries is achieved by convex integration methods, adapting to the present setting the geometric constructions provided in [2] for the isotropic case.

Keywords: Beltrami equation, elliptic equations, gradient integrability.

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1. INTRODUCTION

Let $\Omega \subset \mathbb{R}^2$ be a bounded open domain and let $\sigma \in L^\infty(\Omega; \mathbb{R}^{2 \times 2})$ be uniformly elliptic, i.e.,

$$\sigma \xi \cdot \xi \geq \lambda |\xi|^2 \text{ for every } \xi \in \mathbb{R}^2 \text{ and for a.e. } x \in \Omega,$$

for some $\lambda > 0$. We study the gradient integrability of distributional solutions $u \in W^{1,1}(\Omega)$ to

$$(1.1) \quad \operatorname{div}(\sigma(x) \nabla u(x)) = 0 \quad \text{in } \Omega,$$

in the case when the essential range of σ consists of only two matrices, say σ_1 and σ_2 . It is well-known from Astala's work [1] that there exist exponents q and p , with $1 < q < 2 < p$, such that if $u \in W^{1,q}(\Omega; \mathbb{R})$ is solution to (1.1), then $\nabla u \in L_{\text{weak}}^p(\Omega; \mathbb{R})$. In [9] the optimal exponents p and q have been characterised for every pair of elliptic matrices σ_1 and σ_2 . Denoting by p_{σ_1, σ_2} and q_{σ_1, σ_2} such exponents, whose precise formulas are recalled in Section 2, we summarise the result of [9] in the following theorem.

Theorem 1.1. [9, Theorem 1.4 and Proposition 4.2] *Let $\sigma_1, \sigma_2 \in \mathbb{R}^{2 \times 2}$ be elliptic.*

- i) If $\sigma \in L^\infty(\Omega; \{\sigma_1, \sigma_2\})$ and $u \in W^{1, q_{\sigma_1, \sigma_2}}(\Omega)$ solves (1.1), then $\nabla u \in L_{\text{weak}}^{p_{\sigma_1, \sigma_2}}(\Omega; \mathbb{R}^2)$.*
- ii) There exists $\bar{\sigma} \in L^\infty(\Omega; \{\sigma_1, \sigma_2\})$ and a weak solution $\bar{u} \in W^{1,2}(\Omega)$ to (1.1) with $\sigma = \bar{\sigma}$, satisfying affine boundary conditions and such that $\nabla \bar{u} \notin L^{p_{\sigma_1, \sigma_2}}(\Omega; \mathbb{R}^2)$.*

Theorem 1.1 proves the optimality of the upper exponent p_{σ_1, σ_2} . The objective of this paper is to complement this result by proving the optimality of the lower exponent q_{σ_1, σ_2} . As shown in [9] (and recalled in Section 2), there is no loss of generality in assuming that

$$(1.2) \quad \sigma_1 = \operatorname{diag}(1/K, 1/S_1), \quad \sigma_2 = \operatorname{diag}(K, S_2),$$

with

$$(1.3) \quad K > 1 \quad \text{and} \quad \frac{1}{K} \leq S_j \leq K, \quad j = 1, 2.$$

Thus it suffices to show optimality for this class of coefficients, for which the exponents p_{σ_1, σ_2} and q_{σ_1, σ_2} read as

$$(1.4) \quad q_{\sigma_1, \sigma_2} = \frac{2K}{K+1}, \quad p_{\sigma_1, \sigma_2} = \frac{2K}{K-1}.$$

Our main result is the following

Theorem 1.2. *Let σ_1, σ_2 be defined by (1.2) for some $K > 1$ and $S_1, S_2 \in [1/K, K]$. There exist coefficients $\sigma_n \in L^\infty(\Omega, \{\sigma_1, \sigma_2\})$, exponents $p_n \in [1, \frac{2K}{K+1}]$, functions $u_n \in W^{1,1}(\Omega; \mathbb{R})$ such that*

$$(1.5) \quad \begin{cases} \operatorname{div}(\sigma_n(x)\nabla u_n(x)) = 0 & \text{in } \Omega, \\ u_n(x) = x_1 & \text{on } \partial\Omega, \end{cases}$$

$$(1.6) \quad \nabla u_n \in L_{\text{weak}}^{p_n}(\Omega; \mathbb{R}^2), \quad p_n \rightarrow \frac{2K}{K+1},$$

$$(1.7) \quad \nabla u_n \notin L^{\frac{2K}{K+1}}(\Omega; \mathbb{R}^2).$$

In particular $u_n \in W^{1,q}(\Omega; \mathbb{R})$ for every $q < p_n$, but $\int_{\Omega} |\nabla u_n|^{\frac{2K}{K+1}} dx = \infty$.

Theorem 1.2 was proved in [2] in the case of isotropic coefficients, namely for $\sigma_1 = \frac{1}{K}I$ and $\sigma_2 = KI$. More precisely, in [2] the authors obtain a slightly stronger result by constructing a single coefficient $\sigma \in \{KI, \frac{1}{K}I\}$ and a single function u that satisfies the associated elliptic equation and is such that $\nabla u \in L_{\text{weak}}^{\frac{2K}{K+1}}$, but $\nabla u \notin L^{\frac{2K}{K+1}}$. We follow the method developed in [2], which relies on convex integration as used in [8], and provides an explicit construction of the sequence u_n . The adaptation of such method to the present context turns out to be non-trivial due to the anisotropy of the coefficients (see Remark 5.8). It is not clear how to modify the construction in order to get a stronger result as in [2].

2. CONNECTION WITH THE BELTRAMI EQUATION AND EXPLICIT FORMULAS FOR THE OPTIMAL EXPONENTS

For the reader's convenience we recall in this section how to reduce to the case (1.2) starting from any pair σ_1, σ_2 . We will also give the explicit formulas for p_{σ_1, σ_2} and q_{σ_1, σ_2} .

It is well-known that a solution $u \in W_{loc}^{1,q}$, $q \geq 1$, to the elliptic equation (1.1) can be regarded as the real part of a complex map $f : \Omega \mapsto \mathbb{C}$ which is a $W_{loc}^{1,q}$ solution to a *Beltrami equation*. Precisely, if v is such that

$$(2.1) \quad R_{\frac{\pi}{2}}^T \nabla v = \sigma \nabla u, \quad R_{\frac{\pi}{2}} := \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix},$$

then $f := u + iv$ solves the equation

$$(2.2) \quad f_{\bar{z}} = \mu f_z + \nu \overline{f_z} \quad \text{a.e. in } \Omega,$$

where the so called complex dilatations μ and ν , both belonging to $L^\infty(\Omega; \mathbb{C})$, are given by

$$(2.3) \quad \mu = \frac{\sigma_{22} - \sigma_{11} - i(\sigma_{12} + \sigma_{21})}{1 + \operatorname{Tr} \sigma + \det \sigma}, \quad \nu = \frac{1 - \det \sigma + i(\sigma_{12} - \sigma_{21})}{1 + \operatorname{Tr} \sigma + \det \sigma},$$

and satisfy the ellipticity condition

$$(2.4) \quad \|\mu\| + \|\nu\|_{L^\infty} < 1.$$

The ellipticity (2.4) is often expressed in a different form. Indeed, it implies that there exists $0 \leq k < 1$ such that $\|\mu\| + \|\nu\|_{L^\infty} \leq k < 1$ or equivalently that

$$(2.5) \quad \|\mu\| + \|\nu\|_{L^\infty} \leq \frac{K-1}{K+1},$$

for some $K > 1$. Let us recall that weak solutions to (2.2), (2.5) are called K -quasiregular mappings. Furthermore, we can express σ as a function of μ, ν inverting the algebraic system (2.3),

$$(2.6) \quad \sigma = \begin{pmatrix} \frac{|1-\mu|^2 - |\nu|^2}{|1+\nu|^2 - |\mu|^2} & \frac{2\Im(\nu-\mu)}{|1+\nu|^2 - |\mu|^2} \\ \frac{-2\Im(\nu+\mu)}{|1+\nu|^2 - |\mu|^2} & \frac{|1+\mu|^2 - |\nu|^2}{|1+\nu|^2 - |\mu|^2} \end{pmatrix}.$$

Conversely, if f solves (2.2) with $\mu, \nu \in L^\infty(\Omega, \mathbb{C})$ satisfying (2.4), then its real part is solution to the elliptic equation (1.1) with σ defined by (2.6). Notice that ∇f and ∇u enjoy the same integrability properties. Assume now that $\sigma : \Omega \rightarrow \{\sigma_1, \sigma_2\}$ is a two-phase elliptic coefficient and f is solution to (2.2)-(2.3). Abusing notation, we identify Ω with a subset of \mathbb{R}^2 and $f = u + iv$ with the real mapping $f = (u, v) : \Omega \rightarrow \mathbb{R}^2$. Then, as shown in [9], one can find matrices $A, B \in SL(2)$ (with $SL(2)$ denoting the set of invertible matrices with determinant equal to one) depending only on σ_1 and σ_2 , such that, setting

$$(2.7) \quad \tilde{f}(x) := A^{-1}f(Bx),$$

one has that the function \tilde{f} solves the new Beltrami equation

$$\tilde{f}_{\bar{z}} = \tilde{\mu} f_z + \tilde{\nu} \overline{\tilde{f}_z} \quad \text{a.e. in } B^{-1}(\Omega),$$

and the corresponding $\tilde{\sigma} : B(\Omega) \rightarrow \{\tilde{\sigma}_1, \tilde{\sigma}_2\}$ defined by (2.6) is of the form (1.2):

$$\tilde{\sigma}_1 = \text{diag}(1/K, 1/S_1), \quad \tilde{\sigma}_2 = \text{diag}(K, S_2), \quad K > 1, \quad S_1, S_2 \in [1/K, K].$$

The results in [1] and [12] imply that if $\tilde{f} \in W^{1,q}$, with $q \geq \frac{2K}{K+1}$, then $\nabla \tilde{f} \in L^{\frac{2K}{K-1}}_{\text{weak}}$; in particular, $\tilde{f} \in W^{1,p}$ for each $p < \frac{2K}{K-1}$. Clearly $\nabla \tilde{f}$ enjoys the same integrability properties as ∇f and ∇u .

Finally, we recall the formula for K which will yield the optimal exponents. Denote by d_1 and d_2 the determinant of the symmetric part of σ_1 and σ_2 respectively,

$$d_i := \det \left(\frac{\sigma_i + \sigma_i^T}{2} \right), \quad i = 1, 2,$$

and by $(\sigma_i)_{jk}$ the jk -entry of σ_i . Set

$$m := \frac{1}{\sqrt{d_1 d_2}} \left[(\sigma_2)_{11}(\sigma_1)_{22} + (\sigma_1)_{11}(\sigma_2)_{22} - \frac{1}{2} \left((\sigma_2)_{12} + (\sigma_2)_{21} \right) \left((\sigma_1)_{12} + (\sigma_1)_{21} \right) \right],$$

$$n := \frac{1}{\sqrt{d_1 d_2}} \left[\det \sigma_1 + \det \sigma_2 - \frac{1}{2} \left((\sigma_1)_{21} - (\sigma_1)_{12} \right) \left((\sigma_2)_{21} - (\sigma_2)_{12} \right) \right].$$

Then

$$(2.8) \quad K = \left(\frac{m + \sqrt{m^2 - 4}}{2} \right)^{\frac{1}{2}} \left(\frac{n + \sqrt{n^2 - 4}}{2} \right)^{\frac{1}{2}}.$$

Thus, for any pair of elliptic matrices $\sigma_1, \sigma_2 \in \mathbb{R}^{2 \times 2}$, the explicit formula for the optimal exponents p_{σ_1, σ_2} and q_{σ_1, σ_2} are obtained by plugging (2.8) into (1.4).

3. PRELIMINARIES

3.1. **Conformal coordinates.** For every real matrix $A \in \mathbb{R}^{2 \times 2}$,

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix},$$

we write $A = (a_+, a_-)$, where $a_+, a_- \in \mathbb{C}$ denote its conformal coordinates. By identifying any vector $v = (x, y) \in \mathbb{R}^2$ with the complex number $v = x + iy$, conformal coordinates are defined by the identity

$$(3.1) \quad Av = a_+v + a_- \bar{v}.$$

Here \bar{v} denotes the complex conjugation. From (3.1) we have relations

$$(3.2) \quad a_+ = \frac{a_{11} + a_{22}}{2} + i \frac{a_{21} - a_{12}}{2}, \quad a_- = \frac{a_{11} - a_{22}}{2} + i \frac{a_{21} + a_{12}}{2},$$

and, conversely,

$$(3.3) \quad \begin{aligned} a_{11} &= \Re a_+ + \Re a_-, & a_{12} &= -\Im a_+ + \Im a_-, \\ a_{21} &= \Im a_+ + \Im a_-, & a_{22} &= \Re a_+ - \Re a_-. \end{aligned}$$

Here $\Re z$ and $\Im z$ denote the real and imaginary part of $z \in \mathbb{C}$ respectively. We recall that

$$(3.4) \quad AB = (a_+b_+ + a_- \bar{b}_-, a_+b_- + a_- \bar{b}_+),$$

and $\text{Tr } A = 2\Re a_+$. Moreover

$$(3.5) \quad \begin{aligned} \det(A) &= |a_+|^2 - |a_-|^2, \\ |A|^2 &= 2|a_+|^2 + 2|a_-|^2, \\ \|A\| &= |a_+| + |a_-|, \end{aligned}$$

where $|A|$ and $\|A\|$ denote the Hilbert-Schmidt and the operator norm, respectively.

We also define the second complex dilatation of the map A as

$$(3.6) \quad \mu_A := \frac{a_-}{a_+},$$

and the distortion

$$(3.7) \quad K(A) := \left| \frac{1 + |\mu_A|}{1 - |\mu_A|} \right| = \frac{\|A\|^2}{|\det(A)|}.$$

The last two quantities measure how far A is from being conformal. Following the notation introduced in [2], we define

$$(3.8) \quad E_\Delta := \{A = (a, \mu \bar{a}) : a \in \mathbb{C}, \mu \in \Delta\}$$

for a set $\Delta \subset \mathbb{C} \cup \{\infty\}$; namely, E_Δ is the set of matrices with the second complex dilatation belonging to Δ . In particular E_0 and E_∞ denote the set of conformal and anti-conformal matrices respectively. From (3.4) we have that E_Δ is invariant under precomposition by conformal matrices, that is

$$(3.9) \quad E_\Delta = E_\Delta A \quad \text{for every} \quad A \in E_0 \setminus \{0\}.$$

3.2. Convex integration tools. We denote by $\mathcal{M}(\mathbb{R}^{2 \times 2})$ the set of signed Radon measures on $\mathbb{R}^{2 \times 2}$ having finite mass. By the Riesz's representation theorem we can identify $\mathcal{M}(\mathbb{R}^{2 \times 2})$ with the dual of the space $C_0(\mathbb{R}^{m \times n})$. Given $\nu \in \mathcal{M}(\mathbb{R}^{2 \times 2})$ we define its *barycenter* as

$$\bar{\nu} := \int_{\mathbb{R}^{2 \times 2}} A d\nu(A).$$

We say that a map $f \in C(\bar{\Omega}; \mathbb{R}^2)$ is *piecewise affine* if there exists a countable family of pairwise disjoint open subsets $\Omega_i \subset \Omega$ with $|\partial\Omega_i| = 0$ and

$$\left| \Omega \setminus \bigcup_{i=1}^{\infty} \Omega_i \right| = 0,$$

such that f is affine on each Ω_i . Two matrices $A, B \in \mathbb{R}^{2 \times 2}$ such that $\text{rank}(B - A) = 1$ are said to be *rank-one connected* and the measure $\lambda\delta_A + (1 - \lambda)\delta_B \in \mathcal{M}(\mathbb{R}^{2 \times 2})$ with $\lambda \in [0, 1]$ is called a *laminate of first order* (see also [7], [8], [11]).

Definition 3.1. The family of *laminates of finite order* $\mathcal{L}(\mathbb{R}^{2 \times 2})$ is the smallest family of probability measures in $\mathcal{M}(\mathbb{R}^{2 \times 2})$ satisfying the following conditions:

- (i) $\delta_A \in \mathcal{L}(\mathbb{R}^{2 \times 2})$ for every $A \in \mathbb{R}^{2 \times 2}$;
- (ii) assume that $\sum_{i=1}^N \lambda_i \delta_{A_i} \in \mathcal{L}(\mathbb{R}^{2 \times 2})$ and $A_1 = \lambda B + (1 - \lambda)C$ with $\lambda \in [0, 1]$ and $\text{rank}(B - C) = 1$. Then the probability measure

$$\lambda_1(\lambda\delta_B + (1 - \lambda)\delta_C) + \sum_{i=2}^N \lambda_i \delta_{A_i}$$

is also contained in $\mathcal{L}(\mathbb{R}^{2 \times 2})$.

The process of obtaining new measures via (ii) is called *splitting*. The following proposition provides a fundamental tool to solve differential inclusions by means of convex integration (see e.g. [2, Proposition 2.3] or [8, Lemma 3.2] for a proof).

Proposition 3.2. *Let $\nu = \sum_{i=1}^N \alpha_i \delta_{A_i} \in \mathcal{L}(\mathbb{R}^{2 \times 2})$ be a laminate of finite order with barycenter $\bar{\nu} = A$, that is $A = \sum_{i=1}^N \alpha_i A_i$ with $\sum_{i=1}^N \alpha_i = 1$. Let $\Omega \subset \mathbb{R}^2$ be a bounded open set, $\alpha \in (0, 1)$ and $0 < \delta < \min |A_i - A_j|/2$. Then there exists a piecewise affine Lipschitz map $f: \Omega \rightarrow \mathbb{R}^2$ such that*

- (i) $f(x) = Ax$ on $\partial\Omega$,
- (ii) $[f - A]_{C^\alpha(\bar{\Omega})} < \delta$,
- (iii) $|\{x \in \Omega : |\nabla f(x) - A_i| < \delta\}| = \alpha_i |\Omega|$,
- (iv) $\text{dist}(\nabla f(x), \text{spt } \nu) < \delta$ a.e. in Ω .

3.3. Weak L^p spaces. We recall the definition of weak L^p spaces. Let $f: \Omega \rightarrow \mathbb{R}^2$ be a Lebesgue measurable function. Define the distribution function of f as

$$\lambda_f: (0, \infty) \rightarrow [0, \infty] \quad \text{with} \quad \lambda_f(t) := |\{x \in \Omega : |f(x)| > t\}|.$$

Let $1 \leq p < \infty$, then the following formula holds

$$(3.10) \quad \int_{\Omega} |f(x)|^p dx = p \int_0^{\infty} t^{p-1} \lambda_f(t) dt.$$

Define the quantity

$$[f]_p := \left(\sup_{t>0} t^p \lambda_f(t) \right)^{1/p}$$

and the weak L^p space as

$$L_{\text{weak}}^p(\Omega; \mathbb{R}^2) := \{f: \Omega \rightarrow \mathbb{R}^2 : f \text{ measurable, } [f]_p < \infty\}.$$

L_{weak}^p is a topological vector space and by Chebyshev's inequality we have $[f]_p \leq \|f\|_{L^p}$. In particular this implies $L^p \subset L_{\text{weak}}^p$. Moreover $L_{\text{weak}}^p \subset L^q$ for every $q < p$.

4. PROOF OF THEOREM 1.2

For the rest of this paper, σ_1 and σ_2 are as in (1.2)-(1.3). We start by rewriting (1.1) as a differential inclusion. To this end, define the sets

$$(4.1) \quad T_1 := \left\{ \begin{pmatrix} x & -y \\ S_1^{-1}y & K^{-1}x \end{pmatrix} : x, y \in \mathbb{R} \right\}, \quad T_2 := \left\{ \begin{pmatrix} x & -y \\ S_2y & Kx \end{pmatrix} : x, y \in \mathbb{R} \right\}.$$

Let $\sigma \in L^\infty(\Omega; \{\sigma_1, \sigma_2\})$. It is easy to check (see for example [2, Lemma 3.2]) that u solves (1.1) if and only if f solves the differential inclusion

$$(4.2) \quad \nabla f(x) \in T_1 \cup T_2 \quad \text{a.e. in } \Omega,$$

where $f := (u, v)$ and v is the stream function of u , which is defined, up to an additive constant, by (2.1).

In order to solve the differential inclusion (4.2), it is convenient to use (3.2) and write our target sets in conformal coordinates:

$$(4.3) \quad T_1 = \{(a, d_1(\bar{a})) : a \in \mathbb{C}\}, \quad T_2 = \{(a, -d_2(\bar{a})) : a \in \mathbb{C}\},$$

where the operators $d_j: \mathbb{C} \rightarrow \mathbb{C}$ are defined as

$$(4.4) \quad d_j(a) := k \Re a + i s_j \Im a, \quad \text{with} \quad k := \frac{K-1}{K+1} \quad \text{and} \quad s_j := \frac{S_j-1}{S_j+1}.$$

Conditions (1.3) imply

$$(4.5) \quad 0 < k < 1 \quad \text{and} \quad -k \leq s_j \leq k \quad \text{for } j = 1, 2.$$

Introduce the quantities

$$(4.6) \quad s := \frac{s_1 + s_2}{2} = \frac{S_1 S_2 - 1}{(1 + S_1)(1 + S_2)}$$

$$(4.7) \quad S := \frac{1 + s}{1 - s} = \frac{S_1 + S_2 + 2S_1 S_2}{2 + S_1 + S_2}.$$

By (4.5) we have

$$(4.8) \quad -k \leq s \leq k \quad \text{and} \quad \frac{1}{K} \leq S \leq K.$$

We distinguish three cases.

1. *Case* $s > 0$ (corresponding to $S > 1$). We study this case in Section 5, where we generalise the methods used in [2, Section 3.2]. Observe that this case includes the one studied in [2]. Indeed, for $s = k$ one has that $s_1 = s_2 = k$ and the target sets (4.3) become

$$T_1 = E_k = \{(a, k\bar{a}) : a \in \mathbb{C}\}, \quad T_2 = E_{-k} = \{(a, -k\bar{a}) : a \in \mathbb{C}\},$$

where $E_{\pm k}$ are defined in (3.8). We remark that, in this particular case, the construction provided in Section 5 coincides with the one given in [2, Section 3.2].

2. *Case* $s < 0$ (corresponding to $S < 1$). This case can be reduced to the previous one. Indeed, if we introduce $\hat{s}_j := -s_j$, $\hat{s} := (\hat{s}_1 + \hat{s}_2)/2 > 0$ and the operators $\hat{d}_j(a) := k \Re a + i \hat{s}_j \Im a$ then the target sets (4.3) read as

$$T_1 = \{(a, \hat{d}_1(a)) : a \in \mathbb{C}\}, \quad T_2 = \{(a, -\hat{d}_2(a)) : a \in \mathbb{C}\}.$$

This is the same as the previous case, since the absence of the conjugation does not affect the geometric properties relevant to the constructions of Section 5.

We notice that this case includes $s = -k$ for which the target sets become

$$T_1 = \{(a, ka) : a \in \mathbb{C}\}, \quad T_2 = \{(a, -ka) : a \in \mathbb{C}\}.$$

We remark that in this case, (4.2) coincides with the classical Beltrami equation (see also [2, Remark 3.21]).

3. *Case* $s = 0$ (corresponding to $s_1 = -s_2$, $S_1 = 1/S_2$). This is a degenerate case, in the sense that the constructions provided in Section 5 for $s > 0$ are not well defined. Nonetheless, Theorem 1.2 still holds true. In fact, as already pointed out in [9, Section A.3], by an affine change of variables, the existence of a solution can be deduced by [2, Lemma 4.1, Theorem 4.14], where the authors prove the optimality of the lower critical exponent $\frac{2K}{K+1}$ for the solution of a system in non-divergence form. We remark that in this case Theorem 1.2 actually holds in the stronger sense of exact solutions, namely, there exists $u \in W^{1,1}(\Omega; \mathbb{R})$ solution to (1.5) and such that

$$\nabla u \in L_{\text{weak}}^{\frac{2K}{K+1}}(\Omega; \mathbb{R}^2), \quad \nabla u \notin L^{\frac{2K}{K+1}}(\Omega; \mathbb{R}^2).$$

5. THE CASE $s > 0$

In the present section we prove Theorem 1.2 under the hypothesis that the average s is positive, namely that

$$(5.1) \quad \begin{aligned} 0 < k < 1 \quad \text{and} \quad -s_2 < s_1 \leq s_2, \quad \text{with} \quad 0 < s_2 \leq k, \quad \text{or} \\ 0 < k < 1 \quad \text{and} \quad -s_1 < s_2 \leq s_1, \quad \text{with} \quad 0 < s_1 \leq k. \end{aligned}$$

From (5.1), recalling definitions (4.4), (4.6), (4.7), we have

$$(5.2) \quad 0 < s \leq k, \quad 1 < S \leq K,$$

$$(5.3) \quad 1/S_2 < S_1 \leq S_2, \quad 1 < S_2 \leq K, \quad \text{or} \quad 1/S_1 < S_2 \leq S_1, \quad 1 < S_1 \leq K.$$

In order to prove Theorem 1.2, we will solve the differential inclusion (4.2) by adapting the convex integration program developed in [2, Section 3.2] to the present context. As already pointed out in the Introduction, the anisotropy of the coefficients σ_1, σ_2 poses some technical difficulties in the construction of the so-called staircase laminate, needed to obtain the desired approximate solutions. In fact, the anisotropy of σ_1, σ_2 translates into the lack of conformal invariance (in the sense of (3.9)) of the target sets (4.3), while the constructions provided in [2] heavily rely on the conformal invariance of the target set $E_{\{-k, k\}}$. We point out that the lack of conformal invariance was a source of difficulty in [9] as well, for the proof of the optimality of the upper exponent.

This section is divided as follows. In Section 5.1 we establish some geometrical properties of rank-one lines in $\mathbb{R}^{2 \times 2}$, that will be used in Section 5.2 for the construction of the staircase laminate. For every sufficiently small $\delta > 0$, such laminate allows us to define (in Proposition 5.9) a *piecewise affine* map f that solves the differential inclusion (4.2) up to an arbitrarily small L^∞ error. Moreover f will have the desired integrability properties (see (5.59), that is,

$$\nabla f \in L_{\text{weak}}^p(\Omega; \mathbb{R}^{2 \times 2}), \quad p \in \left(\frac{2K}{K+1} - \delta, \frac{2K}{K+1} \right], \quad \nabla f \notin L^{\frac{2K}{K+1}}(\Omega; \mathbb{R}^{2 \times 2}).$$

Finally, in Theorem 5.10, we remove the L^∞ error introduced in Proposition 5.9, by means of a standard argument (see, e.g., [9, Theorem A.2]).

Throughout this section $c_K > 1$ will denote various constants depending on K, S_1 and S_2 , whose precise value may change from place to place. The complex conjugation is denoted by $J := (0, 1)$ in conformal coordinates, i.e., $Jz = \bar{z}$ for $z \in \mathbb{C}$. Moreover, $R_\theta := (e^{i\theta}, 0) \in SO(2)$ denotes the counter clockwise rotation of angle $\theta \in (-\pi, \pi]$. Define the the argument function

$$\arg z := \theta, \quad \text{where} \quad z = |z|e^{i\theta}, \quad \text{with} \quad \theta \in (-\pi, \pi].$$

Abusing notation we write $\arg R_\theta = \theta$. For $A = (a, b) \in \mathbb{R}^{2 \times 2} \setminus \{0\}$ we set

$$(5.4) \quad \theta_A := -\arg(b - d_1(\bar{a})).$$

5.1. Properties of rank-one lines. In this Section we will establish some geometrical properties of rank-one lines in $\mathbb{R}^{2 \times 2}$. Lemmas 5.2, 5.3 are generalizations of [2, Lemmas 3.14, 3.15] to our target sets (4.3). In Lemmas 5.4, 5.5 we will study certain rank-one lines connecting T to E_∞ , that will be used in Section 5.2 to construct the staircase laminate.

Lemma 5.1. *Let $Q \in T_j$ with $j \in \{1, 2\}$ and T_j as in (4.3). Then*

$$(5.5) \quad \det Q > 0 \quad \text{for} \quad Q \neq 0,$$

$$(5.6) \quad |s_j| \leq |\mu_Q| \leq k,$$

$$(5.7) \quad \max\{S_j, 1/S_j\} \leq K(Q) \leq K.$$

Proof. Let $Q = (q, d_1(\bar{q})) \in T_1$. By (4.5) we have $|s_1||q| \leq |d_1(q)| \leq k|q|$ which readily implies (5.6) and

$$(1 - k^2) |q|^2 \leq \det(Q) \leq (1 - s_1^2) |q|^2 .$$

The last inequality implies (5.5). Finally $K(Q)$ is increasing with respect to $|\mu_Q| \in (0, 1)$, therefore (5.7) follows from (5.6). The proof is analogous if $Q \in T_2$. \square

Lemma 5.2. *Let $A, B \in \mathbb{R}^{2 \times 2}$ with $\det B \neq 0$ and $\det(B - A) = 0$, then*

$$(5.8) \quad |B| \leq \sqrt{2} K(B) |A| .$$

In particular, if $A \in \mathbb{R}^{2 \times 2}$ and $Q \in T_j$, $j \in \{1, 2\}$, are such that $\det(A - Q) = 0$, then

$$\text{dist}(A, T_j) \leq |A - Q| \leq (1 + \sqrt{2}K) \text{dist}(A, T_j) .$$

Proof. The first part of the statement is exactly like in [2, Lemma 3.14]. For the second part, one can easily adapt the proof of [2, Lemma 3.14] to the present context taking into account (5.5) and (5.7). For the reader's convenience we recall the argument. Let $A \in \mathbb{R}^{2 \times 2}$, $Q \in T_1$ and $Q_0 \in T_1$ such that $\text{dist}(A, T_1) = |A - Q_0|$. By (5.5), we can apply the first part of the lemma to $A - Q_0$ and $Q - Q_0$ to get

$$|Q - Q_0| \leq \sqrt{2}K(Q - Q_0)|A - Q_0| \leq \sqrt{2}K|A - Q_0| ,$$

where the last inequality follows from (5.7), since $Q - Q_0 \in T_1$. Therefore

$$|A - Q| \leq |A - Q_0| + |Q - Q_0| \leq (1 + \sqrt{2}K)|A - Q_0| = (1 + \sqrt{2}K) \text{dist}(A, T_1) .$$

The proof for T_2 is analogous. \square

Lemma 5.3. *Every $A = (a, b) \in \mathbb{R}^{2 \times 2} \setminus \{0\}$ lies on a rank-one segment connecting T_1 and E_∞ . Precisely, there exist matrices $Q \in T_1 \setminus \{0\}$ and $P \in E_\infty \setminus \{0\}$, with $\det(P - Q) = 0$, such that $A \in [Q, P]$. We have $P = tJR_{\theta_A}$ for some $t > 0$ and θ_A as in (5.4). Moreover, there exists a constant $c_K > 1$, depending only on K, S_1, S_2 , such that*

$$(5.9) \quad \frac{1}{c_K} |A| \leq |P - Q|, |P|, |Q| \leq c_K |A| .$$

Proof. The proof can be deduced straightforwardly from the one of [2, Lemma 3.15]. We decompose any $A = (a, b)$ as

$$A = (a, d_1(\bar{a})) + \frac{1}{t}(0, tb - td_1(\bar{a})) = Q + \frac{1}{t}P_t ,$$

with $Q \in T_1$ and $P_t \in E_\infty$. The matrices Q and P_t are rank-one connected if and only if $|a| = |d_1(\bar{a}) + t(b - d_1(\bar{a}))|$. Since $\det Q > 0$ for $Q \neq 0$, it is easy to see that there exists only one $t_0 > 0$ such that the last identity is satisfied. We then set $\rho := 1 + 1/t_0$ so that

$$A = \frac{1}{\rho}(\rho Q) + \frac{1}{t_0\rho}(\rho P_{t_0}) .$$

The latter is the desired decomposition, since $\rho Q \in T_1$, $\rho P_{t_0} \in E_\infty$ are rank-one connected, $\rho > 0$ and $\rho^{-1} + (t_0\rho)^{-1} = 1$. Also notice that $\rho P_{t_0} = \rho t_0|b - d_1(\bar{a})|JR_{\theta_A}$ as stated.

Finally let us prove (5.9). Remark that

$$\text{dist}(A, T_1) + \text{dist}(A, E_\infty) \leq |A - P| + |A - Q| = |P - Q| .$$

By the linear independence of T_1 and E_∞ , we get

$$\frac{1}{c_K}|A| \leq |P - Q|.$$

Using Lemma 5.2, (5.5) and (5.7) we obtain

$$|P| \leq c_K|A|, \quad |Q| \leq c_K|A|, \quad |Q| \leq c_K|P|, \quad |P| \leq c_K|Q|.$$

By the triangle inequality,

$$|P - Q| \leq |P| + |Q| \leq (1 + c_K) \min(|P|, |Q|),$$

and (5.9) follows. \square

We now turn our attention to the study of rank-one connections between the target set T and E_∞ .

Lemma 5.4. *Let $R = (r, 0)$ with $|r| = 1$ and $a \in \mathbb{C} \setminus \{0\}$. For $j \in \{1, 2\}$ define*

$$Q_1(a) := \lambda_1(a, d_1(\bar{a})) \in T_1, \quad Q_2(a) := \lambda_2(-a, d_2(\bar{a})) \in T_2,$$

$$(5.10) \quad \lambda_j(a) := \frac{1}{\sqrt{B_j^2(a) + A_j(a) + B_j(a)}},$$

$$(5.11) \quad \begin{cases} A_j(a) := \det(a, d_j(a)) = |a|^2 - |d_j(a)|^2, \\ B_j(a) := \Re(\bar{r} d_j(a)). \end{cases}$$

Then $\lambda_j > 0$, $A_j > 0$ and $\det(Q_j - JR) = 0$. Moreover there exists a constant $c_K > 1$ depending only on K, S_1, S_2 such that

$$(5.12) \quad \frac{1}{c_K} \leq |Q_j(a)| \leq c_K,$$

for every $a \in \mathbb{C} \setminus \{0\}$ and $R \in SO(2)$.

Proof. Condition $\det(Q_j - JR) = 0$ is equivalent to $|\lambda_j a| = |\lambda_j d_j(\bar{a}) - \bar{r}|$, that is

$$(5.13) \quad A_j(a)\lambda_j^2 + 2B_j(a)\lambda_j - 1 = 0$$

with A_j, B_j defined by (5.11). Notice that $A_j > 0$ by (5.5). Therefore λ_j defined in (5.10) solves (5.13) and satisfies $\lambda_j > 0$.

We will now prove (5.12). Since $a \neq 0$, we can write $a = t\omega$ for some $t > 0$ and $\omega \in \mathbb{C}$, with $|\omega| = 1$. We have $A_j(a) = t^2 A_j(\omega)$ and $B_j(a) = t B_j(\omega)$ so that $\lambda_j(a) = \lambda_j(\omega)/t$. Hence

$$(5.14) \quad Q_1(a) = \lambda_1(\omega)(\omega, d_1(\bar{\omega})), \quad Q_2(a) = \lambda_2(\omega)(-\omega, d_2(\bar{\omega})).$$

Since λ_j is continuous and positive in $(\mathbb{C} \setminus \{0\}) \times SO(2)$, (5.12) follows from (5.14). \square

Notation. Let $\theta \in (-\pi, \pi]$. For $R_\theta = (e^{i\theta}, 0) \in SO(2)$, define $x := \cos \theta, y := \sin \theta$ and

$$(5.15) \quad a(R_\theta) := \frac{x}{k} + i \frac{y}{s},$$

where s is defined in (4.6). Identifying $SO(2)$ with the interval $(-\pi, \pi]$, for $j = 1, 2$, we introduce the function

$$(5.16) \quad \lambda_j: (-\pi, \pi] \rightarrow (0, +\infty) \quad \text{defined by} \quad \lambda_j(R_\theta) := \lambda_j(a(R_\theta))$$

with $\lambda_j(a(R_\theta))$ as in (5.10). Furthermore, for $n \in \mathbb{N}$ set

$$(5.17) \quad M_j(R_\theta) := \frac{\lambda_j}{\frac{\lambda_1 + \lambda_2}{2} - \lambda_1 \lambda_2}, \quad l(R_\theta) := \frac{M_1 + M_2}{2} - 1, \quad m := \min_{\theta \in (-\pi, \pi]} \frac{M_2}{2 - M_2}$$

$$L(R_\theta) := \frac{1+l}{1-l}, \quad \beta_n(R_\theta) := 1 - \frac{1+l}{n}, \quad p(R_\theta) := \frac{2L}{L+1}.$$

Lemma 5.5. *For $j = 1, 2$, the functions*

$$\lambda_j: (-\pi, \pi] \rightarrow \left[\frac{s}{1+s_j}, \frac{k}{1+k} \right], \quad l: (-\pi, \pi] \rightarrow [s, k],$$

$$L: (-\pi, \pi] \rightarrow [S, K], \quad p: (-\pi, \pi] \rightarrow \left[\frac{2S}{S+1}, \frac{2K}{K+1} \right],$$

are even, surjective and their periodic extension is C^1 . Furthermore, they are strictly decreasing in $(0, \pi/2)$ and strictly increasing in $(\pi/2, \pi)$, with maximum at $\theta = 0, \pi$ and minimum at $\theta = \pi/2$. Finally

$$(5.18) \quad 0 < M_j < 2, \quad m > 0,$$

$$(5.19) \quad \prod_{j=1}^n \beta_j(R_\theta) = \frac{1}{n^{p(R_\theta)}} + O\left(\frac{1}{n}\right),$$

where $O(1/n) \rightarrow 0$ as $n \rightarrow \infty$ uniformly for $\theta \in (-\pi, \pi]$.

Proof. Let us consider λ_j first. By definitions (5.11), (5.15) and by recalling that $x^2 + y^2 = 1$, we may regard A_j, B_j and λ_j as functions of $x \in [-1, 1]$. In particular,

$$(5.20) \quad A_j(x) = \left(\frac{1-k^2}{k^2} - \frac{1-s_j^2}{s^2} \right) x^2 + \frac{1-s_j^2}{s^2}, \quad B_j(x) = \left(1 - \frac{s_j}{s} \right) x^2 + \frac{s_j}{s}.$$

By symmetry we can restrict to $x \in [0, 1]$. We have three cases:

1. *Case $s_1 = s_2$.* Since $s_1 = s_2 = s$, from (5.20) we compute

$$\lambda_1(x) = \lambda_2(x) = \left(1 + \sqrt{\left(\frac{1}{k^2} - \frac{1}{s^2} \right) x^2 + \frac{1}{s^2}} \right)^{-1}.$$

By (5.1), (5.2) this is a strictly increasing function in $[0, 1]$, and the rest of the thesis for λ_j readily follows.

2. *Case $s_1 < s_2$.* By (5.1) we have

$$(5.21) \quad -s_2 < s_1 < s \quad \text{and} \quad 0 < s < s_2.$$

Relations (5.20) and (5.21) imply that

$$(5.22) \quad A'_j(0) = 0, \quad A'_j(x) < 0, \quad \text{for } x \in (0, 1],$$

$$(5.23) \quad B'_1(0) = 0, \quad B'_1(x) > 0, \quad \text{for } x \in (0, 1],$$

$$(5.24) \quad B'_2(0) = 0, \quad B'_2(x) < 0, \quad \text{for } x \in (0, 1].$$

We claim that

$$(5.25) \quad \lambda'_j(0) = 0, \quad \lambda'_j(x) > 0, \quad \text{for } x \in (0, 1].$$

Before proving (5.25), notice that $\lambda_j(0) = \frac{s}{1+s_j}$ and $\lambda_j(1) = \frac{k}{1+k}$, therefore the surjectivity of λ_j will follow from (5.25). Let us now prove (5.25). For $j = 2$ condition (5.25) is an immediate consequence of the definition of λ_2 and (5.22), (5.24). For $j = 1$ we have

$$(5.26) \quad \lambda'_1(x) = -\frac{1}{\lambda_1^2} \left(\frac{A'_1 + 2B_1B'_1}{2\sqrt{B_1^2 + A_1}} + B'_1 \right)$$

and we immediately see that $\lambda'_1(0) = 0$ by (5.22) and (5.23). Assume now that $x \in (0, 1]$. By (5.23) and (5.26), the claim (5.25) is equivalent to

$$A_1'^2 + 4A_1'B_1B'_1 - 4A_1B_1'^2 > 0, \quad \text{for } x \in (0, 1].$$

After simplifications, the above inequality is equivalent to

$$(5.27) \quad \frac{4f(s_1, s_2)}{k^4(s_1 + s_2)^4} x^2 > 0, \quad \text{for } x \in (0, 1],$$

where $f(s_1, s_2) = abcd$, with

$$\begin{aligned} a &= -2k + (1+k)s_1 + (1-k)s_2, & b &= 2k + (1+k)s_1 + (1-k)s_2, \\ c &= -2k - (1-k)s_1 - (1+k)s_2, & d &= 2k - (1-k)s_1 - (1+k)s_2. \end{aligned}$$

We have that $a, c < 0$ since $s_1 < s_2$ and $b, d > 0$ since $s_1 > -s_2$. Hence (5.27) follows.

3. *Case $s_2 < s_1$.* In particular we have

$$(5.28) \quad -s_1 < s_2 < s \quad \text{and} \quad 0 < s < s_1.$$

This is similar to the previous case. Indeed (5.22) is still true, but for B_j we have

$$(5.29) \quad B'_1(0) = 0, \quad B'_1(x) < 0, \quad \text{for } x \in (0, 1],$$

$$(5.30) \quad B'_2(0) = 0, \quad B'_2(x) > 0, \quad \text{for } x \in (0, 1].$$

This implies (5.25) with $j = 1$. Similarly to the previous case, we can see that (5.25) for $j = 2$ is equivalent to

$$(5.31) \quad \frac{4f(s_2, s_1)}{k^4(s_1 + s_2)^4} x^2 > 0, \quad \text{for } x \in (0, 1].$$

Notice that f is symmetric, therefore (5.31) is a consequence of (5.27).

We will now turn our attention to the function l . Notice that

$$(5.32) \quad l = \frac{1}{1-H} - 1, \quad \text{where} \quad H := \frac{2\lambda_1\lambda_2}{\lambda_1 + \lambda_2} = 2 \left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2} \right)^{-1}$$

is the harmonic mean of λ_1 and λ_2 . Therefore H is differentiable and even. By direct computation we have

$$H' = 2 \frac{\lambda_1' \lambda_2^2 + \lambda_1^2 \lambda_2'}{(\lambda_1 + \lambda_2)^2}.$$

Since $\lambda_j > 0$, by (5.25) we have

$$(5.33) \quad H'(0) = 0, \quad H'(x) > 0, \quad \text{for} \quad x \in (0, 1].$$

Moreover $H(0) = \frac{s}{1+s}$ and $H(1) = \frac{k}{1+k}$. Then from (5.32) we deduce $l(0) = s, l(1) = k$ and the rest of the statement for l .

The statements for L and p follow directly from the properties of l and from the fact that $t \rightarrow \frac{1+t}{1-t}$, $t \rightarrow \frac{2t}{t+1}$ are C^1 and strictly increasing for $0 < t < 1$ and $t > 1$, respectively.

Next we prove (5.18). By (5.1) and the properties of λ_j , we have in particular

$$(5.34) \quad 0 < \lambda_j < \frac{1}{2}, \quad 0 < H < \frac{1}{2},$$

where H is defined in (5.32). Since $\lambda_j > 0$, the inequality $M_j > 0$ is equivalent to $H < 1$, which holds by (5.34). The inequality $M_2 < 2$ is instead equivalent to $\lambda_1(1 - 2\lambda_2) > 0$, which is again true by (5.34). The case $M_1 < 2$ is similar. Finally $m > 0$ follows from $0 < M_2 < 2$ and the continuity of λ_j .

Finally we prove (5.19). By definition we have $1 + l = \frac{2L}{L+1} = p$. By taking the logarithm of $\prod_{j=1}^n \beta_j(R_\theta)$, we see that there exists a constant $c > 0$, depending only on K, S_1, S_2 , such that

$$(5.35) \quad \left| \log \left(\prod_{j=1}^n \beta_j(R_\theta) \right) + p(R_\theta) \log n \right| < c, \quad \text{for every} \quad \theta \in (-\pi, \pi].$$

Estimate (5.35) is uniform because β_j and p are π -periodic and uniformly continuous. \square

5.2. Weak staircase laminate. We are now ready to construct a staircase laminate in the same fashion as [2, Lemma 3.17]. We remark that the construction of this type of laminates, first introduced in [5], has also been used in [3] and [4] in connection with the problem of regularity for rank-one convex functions and in [6] and [10] for constructing Sobolev homeomorphisms with gradients of law rank.

The steps of our staircase will be the sets

$$\mathcal{S}_n := nJSO(2) = \{(0, ne^{i\theta}) : \theta \in (-\pi, \pi]\}, \quad n \geq 1.$$

For $0 < \delta < \pi/2$ we introduce the set

$$E_\infty^\delta := \{(0, z) \in E_\infty : |\arg z| < \delta\}, \quad \mathcal{S}_n^\delta := \mathcal{S}_n \cap E_\infty^\delta.$$

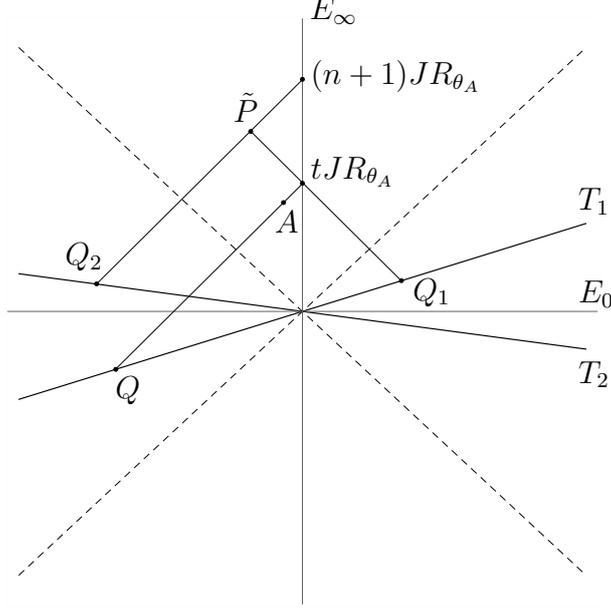


FIGURE 1. Weak staircase laminate.

Lemma 5.6. *Let $0 < \delta < \pi/4$ and $0 < \rho < \min\{m, \frac{1}{2}\}$, with $m > 0$ defined in (5.17). There exists a constant $c_K > 1$ depending only on K, S_1, S_2 , such that for every $A = (a, b) \in \mathbb{R}^{2 \times 2}$ satisfying*

$$(5.36) \quad \text{dist}(A, \mathcal{S}_n) < \rho,$$

there exists a laminate of third order ν_A , such that:

- (i) $\bar{\nu}_A = A$,
- (ii) $\text{spt } \nu_A \subset T \cup \mathcal{S}_{n+1}$,
- (iii) $\text{spt } \nu_A \subset \{\xi \in \mathbb{R}^{2 \times 2} : c_K^{-1}n < |\xi| < c_K n\}$,
- (iv) $\text{spt } \nu_A \cap \mathcal{S}_{n+1} = \{(n+1)JR\}$, with $R = R_{\theta_A}$ as in (5.4).

Moreover

$$(5.37) \quad \left(1 - c_K \frac{\rho}{n}\right) \beta_n(R) \leq \nu_A(\mathcal{S}_{n+1}) \leq \left(1 + c_K \frac{\rho}{n}\right) \beta_{n+2}(R),$$

where β_n is defined in (5.17). If in addition $n \geq 2$ and

$$(5.38) \quad \text{dist}(A, \mathcal{S}_n^\delta) < \rho,$$

then

$$(5.39) \quad |\arg R| = |\theta_A| < \delta + \rho.$$

In particular $\text{spt } \nu_A \subset T \cup \mathcal{S}_{n+1}^{\delta+\rho}$.

Proof. Let us start by defining ν_A . From Lemma 5.3 there exist $c_K > 1$ and non zero matrices $Q \in T_1$, $P \in E_\infty$, such that $\det(P - Q) = 0$,

$$(5.40) \quad A = \mu_1 Q + (1 - \mu_1)P, \quad \text{for some } \mu_1 \in [0, 1],$$

$$(5.41) \quad \frac{1}{c_K} |A| \leq |P - Q|, |P|, |Q| \leq c_K |A|.$$

Moreover $P = tJR$ with $R = R_{\theta_A} = (r, 0)$ as in (5.4) and $t > 0$. We will estimate t . By (5.36), there exists $\tilde{R} \in SO(2)$ such that $|A - nJ\tilde{R}| < \rho$. Applying Lemma 5.2 to $A - nJ\tilde{R}$ and $P - nJ\tilde{R}$ yields

$$(5.42) \quad |P - nJ\tilde{R}| < \sqrt{2}\rho,$$

since $P - nJ\tilde{R} \in E_\infty$. Hence from (5.42) we get

$$(5.43) \quad |t - n| < \rho,$$

since $|JR| = |J\tilde{R}| = \sqrt{2}$. We also have

$$(5.44) \quad \mu_1 = \frac{|A - Q|}{|P - Q|} \geq 1 - \frac{|P - A|}{|P - Q|} \geq 1 - c_K \frac{\rho}{n},$$

since $|P - A| < 3\rho$ and $|P - Q| > n/c_K$, by (5.38), (5.41), (5.42).

Next we split P in order to “climb” one step of the staircase (see Figure 1). Define $x := \cos \theta_A$, $y := \sin \theta_A$ and

$$a := \frac{x}{k} + i \frac{y}{s},$$

as in (5.15). Moreover set

$$Q_1 := \lambda_1(a, d_1(\bar{a})), \quad Q_2 := \lambda_2(-a, d_2(\bar{a})).$$

Here λ_1, λ_2 are chosen as in (5.10), so that $Q_j \in T_j$ and, by Lemma 5.4, $\det(Q_j - JR) = 0$. Furthermore, set

$$(5.45) \quad \begin{cases} \mu_2 := \frac{M_2 - (t - n)M_2}{2n + M_2 + (t - n)(2 - M_2)}, \\ \mu_3 := \frac{M_1 - (t - n)M_1}{2(n + 1)}, \end{cases}$$

with M_j as in (5.17). With the above choices we have

$$(5.46) \quad \begin{cases} tJR = \mu_2 tQ_1 + (1 - \mu_2)\tilde{P}, \\ \tilde{P} = \mu_3(n + 1)Q_2 + (1 - \mu_3)(n + 1)JR, \end{cases}$$

and $\mu_2, \mu_3 \in [0, 1]$ by (5.18). In order to check (5.46), we solve the first equation in \tilde{P} to get

$$(5.47) \quad \gamma_2 tJR + (1 - \gamma_2)tQ_1 = \gamma_3(n + 1)Q_2 + (1 - \gamma_3)(n + 1)JR,$$

with $\mu_2 = 1 - 1/\gamma_2$ and $\mu_3 = \gamma_3$. Equating the first conformal coordinate of both sides of (5.47) yields

$$(5.48) \quad \gamma_2 = 1 + \gamma_3 \frac{n+1}{t} \frac{\lambda_2}{\lambda_1}.$$

Substituting (5.48) in the second component of (5.47) gives us

$$(5.49) \quad \gamma_3 (\lambda_1 + \lambda_2 - \lambda_1 \lambda_2 (d_1(a) + d_2(a)) r^{-1}) = \frac{1 - (t-n)}{n+1} \lambda_1.$$

By (5.15), $d_1(a) + d_2(a) = 2r$ and equation (5.49) yields

$$(5.50) \quad \gamma_3 = \frac{1 - (t-n)}{n+1} \frac{\lambda_1}{\lambda_1 + \lambda_2 - 2\lambda_1 \lambda_2} = \frac{1 - (t-n)}{2(n+1)} M_1.$$

Equations (5.48) and (5.50) give us (5.45). Therefore, by (5.40) and (5.46), the measure

$$\nu_A := \mu_1 \delta_Q + (1 - \mu_1) (\mu_2 \delta_{tQ_1} + (1 - \mu_2) (\mu_3 \delta_{(n+1)Q_2} + (1 - \mu_3) \delta_{(n+1)JR}))$$

defines a laminate of third order with barycenter A , supported in $T_1 \cup T_2 \cup \mathcal{S}_{n+1}$ and such that $\text{spt } \nu_A \cap \mathcal{S}_{n+1} = \{(n+1)JR\}$ with $R = R_{\theta_A}$. Moreover

$$\text{spt } \nu_A \subset \{\xi \in \mathbb{R}^{2 \times 2} : c_K^{-1} n < |\xi| < c_K n\},$$

since $c_K^{-1} n < |Q| < c_K n$ by (5.36), (5.41) and

$$c_K^{-1} n < |tQ_1|, |(n+1)Q_2| < c_K n$$

by (5.43), (5.12). Next we prove (5.37) by estimating

$$(5.51) \quad \nu_A(\mathcal{S}_{n+1}) = \mu_1(1 - \mu_2)(1 - \mu_3).$$

Notice that $\nu_A(\mathcal{S}_{n+1})$ depends on R . For small ρ , we have

$$\mu_2 = \frac{M_2}{2n} + \rho O\left(\frac{1}{n}\right), \quad \mu_3 = \frac{M_1}{2n} + \rho O\left(\frac{1}{n}\right),$$

so that

$$(1 - \mu_2)(1 - \mu_3) = 1 - \frac{M_1 + M_2}{2n} + \rho O\left(\frac{1}{n^2}\right) = 1 - \frac{1+l}{n} + \rho O\left(\frac{1}{n^2}\right),$$

with l as in (5.17). Although this gives the right asymptotic, we will need to estimate (5.51) for every $n \in \mathbb{N}$. By direct calculation

$$(1 - \mu_2)(1 - \mu_3) = \frac{n + (t-n)}{n+1} \frac{2n + 2 - M_1 + (t-n)M_1}{2n + M_2 + (t-n)(2 - M_2)},$$

so that

$$(5.52) \quad (1 - \mu_2)(1 - \mu_3) = \left(1 + \frac{t-n}{n}\right) \left(1 - \frac{1}{n+1}\right) \left(1 - \frac{2l(1 - (t-n))}{2n + M_2 + (t-n)(2 - M_2)}\right).$$

Let us bound (5.52) from above. Recall that $t - n < \rho < 1$ and $2 - M_2 > 0$, by (5.18), so the denominator of the third factor in (5.52) is bounded from above by $2(n + 1)$ and

$$(5.53) \quad \begin{aligned} (1 - \mu_2)(1 - \mu_3) &\leq \left(1 + \frac{\rho}{n}\right) \left(1 - \frac{1}{n+1}\right) \left(1 - \frac{l}{n+1} + l \frac{\rho}{n+1}\right) \\ &\leq \left(1 + c_K \frac{\rho}{n}\right) \left(1 - \frac{1}{n+1}\right) \left(1 - \frac{l}{n+1}\right), \end{aligned}$$

where $c_K > 1$ is such that

$$l \frac{\rho}{n+1} \left(1 + \frac{\rho}{n}\right) \leq (c_K - 1) \frac{\rho}{n} \left(1 - \frac{l}{n+1}\right).$$

Moreover

$$(5.54) \quad \left(1 - \frac{1}{n+1}\right) \left(1 - \frac{l}{n+1}\right) = 1 - \frac{1+l}{n+1} + \frac{l}{(n+1)^2} \leq 1 - \frac{1+l}{n+2} = \beta_{n+2}(R).$$

The upper bound in (5.37) follows from (5.53) and (5.54).

Let us now bound (5.52) from below. We can estimate from below the denominator in the third factor of (5.52) with $2n$, since $t - n > -\rho$ by (5.43) and the assumption that $\rho < m$ with m as in (5.17). Therefore

$$(5.55) \quad \begin{aligned} (1 - \mu_2)(1 - \mu_3) &\geq \left(1 - \frac{\rho}{n}\right) \left(1 - \frac{1}{n+1}\right) \left(1 - \frac{l}{n} - l \frac{\rho}{n}\right) \\ &\geq \left(1 - c_K \frac{\rho}{n}\right) \left(1 - \frac{1}{n+1}\right) \left(1 - \frac{l}{n}\right), \end{aligned}$$

if we choose $c_K > 1$ such that

$$\left(1 - \frac{\rho}{n}\right) l \leq (c_K - 1) \left(1 - \frac{l}{n}\right).$$

Finally

$$(5.56) \quad \left(1 - \frac{1}{n+1}\right) \left(1 - \frac{l}{n}\right) \geq 1 - \frac{1+l}{n} = \beta_n(R).$$

The lower bound in (5.37) follows from (5.55) and (5.56).

Finally, the last part of the statement follows from a simple geometrical argument, recalling that $\arg R = \theta_A = -\arg(b - d_1(\bar{a}))$ and using hypothesis (5.38). \square

Remark 5.7. *By iteratively applying Lemma 5.6, one can obtain, for every $R_\theta \in SO(2)$, a sequence of laminates of finite order $\nu_n \in \mathcal{L}(\mathbb{R}^{2 \times 2})$ that satisfies $\bar{\nu}_n = JR_\theta$, $\text{spt } \nu_n \subset T_1 \cup T_2 \cup \mathcal{S}_{n+1}$, and*

$$(5.57) \quad \lim_{n \rightarrow \infty} \int_{\mathbb{R}^{2 \times 2}} |\lambda|^{p(R_\theta)} d\nu_n(\lambda) = \infty,$$

where $p(R_\theta) \in \left[\frac{2S}{S+1}, \frac{2K}{K+1}\right]$ is the function defined in (5.17). Indeed, setting $A = JR_\theta$ and iterating the construction of Lemma 5.6, yields $\nu_n \in \mathcal{L}(\mathbb{R}^{2 \times 2})$ such that $\bar{\nu}_n = JR_\theta$ and $\text{spt } \nu_n \subset T_1 \cup T_2 \cup \mathcal{S}_{n+1}$. Notice that ν_n contains the term $\prod_{j=1}^n (1 - \mu_2^j)(1 - \mu_3^j) \delta_{(n+1)JR_\theta}$,

with μ_2^j, μ_3^j as defined in (5.45). Therefore, using (5.19) and (5.37) (with $\rho = 0$), we obtain

$$(5.58) \quad \prod_{j=1}^n (1 - \mu_2^j)(1 - \mu_3^j) \approx \prod_{j=1}^n \beta_j(R_\theta) \approx \frac{1}{n^{p(R_\theta)}}$$

which implies (5.57).

Remark 5.8. In the isotropic case $S = K$, the laminate ν_A provided by Lemma 5.6 coincides with the one in [2, Lemma 3.16]. In particular, the growth condition (5.37) is independent of the initial point A , and it reads as

$$\left(1 - c_K \frac{\rho}{n}\right) \beta_n(I) \leq \nu_A(\mathcal{S}_{n+1}) \leq \left(1 + c_K \frac{\rho}{n}\right) \beta_{n+2}(I), \quad \beta_n(I) = 1 - \frac{1+k}{n}.$$

Moreover, by Remark 5.7, for every $R_\theta \in SO(2)$, JR_θ is the center of mass of a sequence of laminates of finite order such that (5.57) holds with $p(R_\theta) \equiv \frac{2K}{K+1}$, which gives the desired growth rate.

In contrast, in the anisotropic case $1 < S < K$, the growth rate of the laminates explicitly depends on the argument of the barycenter JR_θ . The desired growth rate corresponds to $\theta = 0$, that is, the center of mass has to be J .

In constructing approximate solutions with the desired integrability properties, it is then crucial to be able to select rotations whose angle lies in an arbitrarily small neighbourhood of $\theta = 0$.

We now proceed to show the existence of a *piecewise affine* map f that solves the differential inclusion (4.2) up to an arbitrarily small L^∞ error. Such map will have the integrability properties given by (5.59).

Proposition 5.9. Let $\Omega \subset \mathbb{R}^2$ be an open bounded domain. Let $K > 1$, $\alpha \in (0, 1)$, $\varepsilon > 0$, $0 < \delta_0 < \frac{2K}{K+1} - \frac{2S}{S+1}$, $\gamma > 0$. There exist a constant $c_{K, \delta_0} > 1$, depending only on K, S_1, S_2, δ_0 , and a piecewise affine map $f \in W^{1,1}(\Omega; \mathbb{R}^2) \cap C^\alpha(\bar{\Omega}; \mathbb{R}^2)$, such that

- (i) $f(x) = Jx$ on $\partial\Omega$,
- (ii) $[f - Jx]_{C^\alpha(\bar{\Omega})} < \varepsilon$,
- (iii) $\text{dist}(\nabla f(x), T) < \gamma$ a.e. in Ω .

Moreover

$$(5.59) \quad \frac{1}{c_{K, \delta_0}} t^{-\frac{2K}{K+1}} < \frac{|\{x \in \Omega : |\nabla f(x)| > t\}|}{|\Omega|} < c_{K, \delta_0} t^{-p},$$

where $p \in \left(\frac{2K}{K+1} - \delta_0, \frac{2K}{K+1}\right]$. That is, $\nabla f \in L_{\text{weak}}^p(\Omega; \mathbb{R}^{2 \times 2})$ and $\nabla f \notin L^{\frac{2K}{K+1}}(\Omega; \mathbb{R}^{2 \times 2})$. In particular $f \in W^{1,q}(\Omega; \mathbb{R}^2)$ for every $q < p$, but $\int_\Omega |\nabla f(x)|^{\frac{2K}{K+1}} dx = \infty$.

Proof. By Lemma 5.5 the function $p: (-\pi, \pi) \rightarrow \left[\frac{2S}{S+1}, \frac{2K}{K+1}\right]$ is uniformly continuous. Let $\alpha: [0, \infty) \rightarrow [0, \infty)$ be its modulus of continuity. Fix $0 < \delta < \pi/4$ such that

$$(5.60) \quad \alpha(\delta) < \delta_0.$$

Let $\{\rho_n\}$ be a strictly decreasing positive sequence satisfying

$$(5.61) \quad \rho_1 < \frac{1}{4} \min\{m, c_K^{-1}, \text{dist}(\mathcal{S}_1, T), \gamma\}, \quad \rho_n < \frac{\delta}{4} 2^{-n},$$

where $m > 0$ and $c_K > 1$ are the constants from Lemma 5.6. Define $\{\delta_n\}$ as

$$(5.62) \quad \delta_1 := 0 \quad \text{and} \quad \delta_n := \sum_{j=1}^{n-1} \rho_j \quad \text{for } n \geq 2.$$

In particular from (5.61),(5.62) it follows that

$$(5.63) \quad \delta_n < \frac{\delta}{2}, \quad \text{for every } n \in \mathbb{N}.$$

Step 1. Similarly to the proof of [2, Proposition 3.17], by repeatedly combining Lemma 5.6 and Proposition 3.2, we will prove the following statement:

Claim. There exist sequences of piecewise constant functions $\tau_n: \Omega \rightarrow (0, \infty)$ and piecewise affine Lipschitz mappings $f_n: \Omega \rightarrow \mathbb{R}^2$, such that

- (a) $f_n(x) = Jx$ on $\partial\Omega$,
- (b) $[f_n - Jx]_{C^\alpha(\bar{\Omega})} < (1 - 2^{-n})\varepsilon$,
- (c) $\text{dist}(\nabla f_n(x), T \cup \mathcal{S}_n^{\delta_n}) < \tau_n(x)$ a.e. in Ω ,
- (d) $\tau_n(x) = \rho_n$ in Ω_n ,

where

$$\Omega_n := \{x \in \Omega : \text{dist}(\nabla f_n(x), T) \geq \rho_n\}.$$

Moreover

$$(5.64) \quad \prod_{j=1}^{n-1} \left(1 - c_K \frac{\rho_j}{j}\right) \beta_j(R_0) \leq \frac{|\Omega_n|}{|\Omega|} \leq \prod_{j=1}^{n-1} \left(1 + c_K \frac{\rho_j}{j}\right) \beta_{j+2}(R_\delta).$$

Proof of the claim. We proceed by induction. Set $f_1(x) := Jx$ and $\tau_1(x) := \rho_1$ for every $x \in \Omega$. Since $J \in \mathcal{S}_1^0$, then f_1 satisfies (a)-(c). Also, $\rho_1 < \text{dist}(T, \mathcal{S}_1)/4$ by (5.61), so $\Omega_1 = \Omega$ and (d), (5.64) follow.

Assume now that f_n and τ_n satisfy the inductive hypothesis. We will first define f_{n+1} by modifying f_n on the set Ω_n . Since f_n is piecewise affine we have a decomposition of Ω_n into pairwise disjoint open subsets $\Omega_{n,i}$ such that

$$(5.65) \quad \left| \Omega_n \setminus \bigcup_{i=1}^{\infty} \Omega_{n,i} \right| = 0,$$

with $f_n(x) = A_i x + b_i$ in $\Omega_{n,i}$, for some $A_i \in \mathbb{R}^{2 \times 2}$ and $b_i \in \mathbb{R}^2$. Moreover

$$(5.66) \quad \text{dist}(A_i, \mathcal{S}_n^{\delta_n}) < \rho_n$$

by (c) and (d). Since (5.66) and (5.61) hold, we can invoke Lemma 5.6 to obtain a laminate ν_{A_i} and a rotation $R^i = R_{\theta_{A_i}}$ satisfying, in particular, $\bar{\nu}_{A_i} = A_i$,

$$(5.67) \quad |\arg R^i| = |\theta_{A_i}| < \delta_{n+1},$$

$$(5.68) \quad \text{spt } \nu_{A_i} \subset T \cup \mathcal{S}_{n+1}^{\delta_{n+1}},$$

since $\delta_{n+1} = \delta_n + \rho_n$ by (5.62). By applying Proposition 3.2 to ν_{A_i} and by taking into account (5.68), we obtain a piecewise affine Lipschitz mapping $g_i: \Omega_{n,i} \rightarrow \mathbb{R}^2$, such that

$$(e) \quad g_i(x) = A_i x + b_i \text{ on } \partial\Omega_{n,i},$$

$$(f) \quad [g_i - f_n]_{C^\alpha(\bar{\Omega}_{n,i})} < 2^{-(n+1+i)} \varepsilon,$$

$$(g) \quad c_K^{-1} n < |\nabla g_i(x)| < c_K n \text{ a.e. in } \Omega_{n,i},$$

$$(h) \quad \text{dist}(\nabla g_i(x), T \cup \mathcal{S}_{n+1}^{\delta_{n+1}}) < \rho_{n+1} \text{ a.e. in } \Omega_{n,i}.$$

Moreover

$$(5.69) \quad \left(1 - c_K \frac{\rho_n}{n}\right) \beta_n(R^i) \leq \frac{|\omega_{n,i}|}{|\Omega_{n,i}|} \leq \left(1 + c_K \frac{\rho_n}{n}\right) \beta_{n+2}(R^i),$$

with

$$\omega_{n,i} := \left| \left\{ x \in \Omega_{n,i} : \text{dist}(\nabla g_i(x), \mathcal{S}_{n+1}^{\delta_{n+1}}) < \rho_{n+1} \right\} \right|.$$

Set

$$f_{n+1}(x) := \begin{cases} f_n(x) & \text{if } x \in \Omega \setminus \Omega_n, \\ g_i(x) & \text{if } x \in \Omega_{n,i}. \end{cases}$$

Since Ω_{n+1} is well defined, we can also introduce

$$\tau_{n+1}(x) := \begin{cases} \tau_n(x) & \text{for } x \in \Omega \setminus \Omega_{n+1}, \\ \rho_{n+1} & \text{for } x \in \Omega_{n+1}, \end{cases}$$

so that (d) holds. From (e) we have $f_{n+1}(x) = Jx$ on $\partial\Omega$. From (f) we get $[f_{n+1} - f_n]_{C^\alpha(\bar{\Omega})} < 2^{-(n+1)} \varepsilon$ so that (b) follows. (c) is a direct consequence of (d), (h), and the fact that ρ_n is strictly decreasing. Finally let us prove (5.64). First notice that the sets $\omega_{n,i}$ are pairwise disjoint. By (5.61), in particular we have $\rho_{n+1} < \text{dist}(T, \mathcal{S}_1)/4$, so that

$$(5.70) \quad \left| \Omega_{n+1} \setminus \bigcup_{i=1}^{\infty} \omega_{n,i} \right| = 0.$$

By (5.67) and (5.63) we have $|\arg R^i| < \delta$. Then by the properties of β_n (see Lemma 5.5),

$$(5.71) \quad \beta_n(R^i) \geq \beta_n(R_0) \quad \text{and} \quad \beta_{n+2}(R^i) \leq \beta_{n+2}(R_\delta).$$

Using (5.71), (5.65), (5.70) in (5.64) yields

$$|\Omega_n| \left(1 - c_K \frac{\rho_n}{n}\right) \beta_j(R_0) \leq |\Omega_{n+1}| \leq |\Omega_n| \left(1 + c_K \frac{\rho_n}{n}\right) \beta_{j+2}(R_\delta),$$

and (5.64) follows.

Step 2. Notice that on $\Omega \setminus \Omega_n$ we have that $\nabla f_{n+1} = \nabla f_n$ almost everywhere, so $\Omega_{n+1} \subset \Omega_n$. Therefore $\{f_n\}$ is obtained by modification on a nested sequence of open sets, satisfying

$$\prod_{j=1}^{n-1} \left(1 - c_K \frac{\rho_j}{j}\right) \beta_j(R_0) \leq \frac{|\Omega_n|}{|\Omega|} \leq \prod_{j=1}^{n-1} \left(1 + c_K \frac{\rho_j}{j}\right) \beta_{j+2}(R_\delta).$$

By (5.61) we have $\rho_n < \min\{2^{-n} \delta, c_K^{-1}\}/4$, so that

$$\prod_{j=1}^{\infty} \left(1 - c_K \frac{\rho_j}{j}\right) = c_1, \quad \prod_{j=1}^{\infty} \left(1 + c_K \frac{\rho_j}{j}\right) = c_2,$$

with $0 < c_1 < c_2 < \infty$, depending only on K, S_1, S_2, δ (and hence from δ_0 , by (5.60)). Moreover, from Lemma 5.5,

$$\prod_{j=1}^n \beta_j(R_\theta) = n^{-p(R_\theta)} + O\left(\frac{1}{n}\right), \quad \text{uniformly in } (-\pi, \pi].$$

Therefore, there exists a constant $c_{K,\delta_0} > 1$ depending only on K, S_1, S_2, δ_0 , such that

$$(5.72) \quad \frac{1}{c_{K,\delta_0}} n^{-\frac{2K}{K+1}} \leq |\Omega_n| \leq c_{K,\delta_0} n^{-p_{\delta_0}},$$

since $p(R_0) = \frac{2K}{K+1}$. Here $p_{\delta_0} := p(R_\delta)$. Notice that, by (5.60), $p_{\delta_0} \in \left(\frac{2K}{K+1} - \delta_0, \frac{2K}{K+1}\right]$, since p is strictly decreasing in $[0, \pi/2]$.

From (5.72), in particular we deduce $|\Omega_n| \rightarrow 0$. Therefore $f_n \rightarrow f$ almost everywhere in Ω , with f piecewise affine. Furthermore f satisfies (i)-(iii) by construction.

We are left to estimate the distribution function of ∇f . By (g) we have that

$$|\nabla f(x)| > \frac{n}{c_{K,\delta_0}} \quad \text{in } \Omega_n \quad \text{and} \quad |\nabla f(x)| < c_{K,\delta_0} n \quad \text{in } \Omega \setminus \Omega_n.$$

For a fixed $t > c_{K,\delta_0}$, let $n_1 := [c_{K,\delta_0} t]$ and $n_2 := [c_{K,\delta_0}^{-1} t]$, where $[\cdot]$ denotes the integer part function. Therefore

$$\Omega_{n_1+1} \subset \{x \in \Omega : |\nabla f(x)| > t\} \subset \Omega_{n_2}$$

and (5.59) follows from (5.72), with $p = p_{\delta_0}$. Lastly, (5.59) implies that ∇f_n is uniformly bounded in L^1 , so that $f \in W^{1,1}(\Omega; \mathbb{R}^2)$ by dominated convergence. \square

We remark that the constant c_{K,δ_0} in (5.59) is monotonically increasing as a function of δ_0 , that is $c_{K,\delta_1} \leq c_{K,\delta_2}$ if $\delta_1 \leq \delta_2$.

We now proceed with the construction of exact solutions to (4.2). We will follow a standard argument (see, e.g., [5, Remark 6.3], [9, Theorem A.2]).

Theorem 5.10. *Let σ_1, σ_2 be defined by (1.2) for some K, S_1, S_2 as in (5.3) and S as in (4.7). There exist coefficients $\sigma_n \in L^\infty(\Omega; \{\sigma_1, \sigma_2\})$, exponents $p_n \in \left[\frac{2S}{S+1}, \frac{2K}{K+1}\right]$, functions*

$u_n \in W^{1,1}(\Omega; \mathbb{R})$, such that

$$(5.73) \quad \begin{cases} \operatorname{div}(\sigma_n(x)\nabla u_n(x)) = 0 & \text{in } \Omega, \\ u_n(x) = x_1 & \text{on } \partial\Omega, \end{cases}$$

$$(5.74) \quad \nabla u_n \in L_{\text{weak}}^{p_n}(\Omega; \mathbb{R}^2), \quad p_n \rightarrow \frac{2K}{K+1},$$

$$(5.75) \quad \nabla u_n \notin L^{\frac{2K}{K+1}}(\Omega; \mathbb{R}^2).$$

In particular $u_n \in W^{1,q}(\Omega; \mathbb{R})$ for every $q < p_n$, but $\int_{\Omega} |\nabla u_n|^{\frac{2K}{K+1}} dx = \infty$.

Proof. By Proposition 5.9 there exist sequences $f_n \in W^{1,1}(\Omega; \mathbb{R}^2) \cap C^\alpha(\bar{\Omega}; \mathbb{R}^2)$, $\gamma_n \searrow 0$, $p_n \in [\frac{2S}{S+1}, \frac{2K}{K+1}]$, such that, $f_n(x) = Jx$ on $\partial\Omega$,

$$(5.76) \quad \operatorname{dist}(\nabla f_n(x), T_1 \cup T_2) < \gamma_n \quad \text{a.e. in } \Omega,$$

$$(5.77) \quad \nabla f_n \in L_{\text{weak}}^{p_n}(\Omega; \mathbb{R}^{2 \times 2}), \quad p_n \rightarrow \frac{2K}{K+1}, \quad \nabla f_n \notin L^{\frac{2K}{K+1}}(\Omega; \mathbb{R}^{2 \times 2}).$$

In euclidean coordinates, condition (5.76) implies that

$$(5.78) \quad \begin{pmatrix} \nabla f_n^1(x) \\ \nabla f_n^2(x) \end{pmatrix} = \begin{pmatrix} E_n(x) \\ R_{\frac{\pi}{2}} \sigma_n(x) E_n(x) \end{pmatrix} + \begin{pmatrix} a_n(x) \\ b_n(x) \end{pmatrix} \quad \text{a.e. in } \Omega$$

with $f_n = (f_n^1, f_n^2)$, $\sigma_n := \sigma_1 \chi_{\{\nabla f \in T_1\}} + \sigma_2 \chi_{\{\nabla f \in T_2\}}$, $E_n: \Omega \rightarrow \mathbb{R}^2$, $R_{\frac{\pi}{2}} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$ and

$$(5.79) \quad a_n, b_n \rightarrow 0 \quad \text{in } L^\infty(\Omega; \mathbb{R}^2).$$

The boundary condition $f_n = Jx$ reads $f_n^1 = x_1$ and $f_n^2 = -x_2$. We set $u_n := f_n^1 + v_n$, where $v_n \in H_0^1(\Omega, \mathbb{R})$ is the unique solution to

$$\operatorname{div}(\sigma_n \nabla v) = -\operatorname{div}(\sigma_n a_n - R_{\frac{\pi}{2}}^T b_n).$$

Notice that v_n is uniformly bounded in H^1 by (5.79). Since (5.78) holds, it is immediate to check that $\operatorname{div}(\sigma_n \nabla u_n) = \operatorname{div}(R_{\frac{\pi}{2}}^T \nabla f_n^2) = 0$, so that u_n is a solution of (5.73). Finally, the regularity thesis (5.74), (5.75), follows from the definition of u_n and the fact that $v_n \in H_0^1(\Omega; \mathbb{R})$ and f_n^1 satisfies (5.77) with $1 < p_n < 2$. \square

REFERENCES

- [1] K. Astala. Area distortion of quasiconformal mappings. *Acta Math.*, 173(1):37–60, 1994.
- [2] K. Astala, D. Faraco, and L. Székelyhidi. Convex integration and the L^p theory of elliptic equations. *Ann. Scuola Norm. Sup. Pisa Cl. Sci.*, 5(7):1–50, 2008.
- [3] S. Conti, D. Faraco, and F. Maggi. A new approach to counterexamples to L^1 estimates: Korn's inequality, geometric rigidity, and regularity for gradients of separately convex functions. *Arch. Ration. Mech. Anal.*, 175(2):287–300, 2005.
- [4] S. Conti, D. Faraco, F. Maggi, and S. Müller. Rank-one convex functions on 2×2 symmetric matrices and laminates on rank-three lines. *Calc. Var. Partial Differential Equations*, 24(4):479–493, 2005.
- [5] D. Faraco. Milton's conjecture on the regularity of solutions to isotropic equations. *Ann. Inst. H. Poincaré Anal. Non Linéaire*, 20(5):889–909, 2003.

- [6] D. Faraco, C. Mora-Corral, and M. Oliva. Sobolev homeomorphisms with gradients of low rank via laminates. *Advances in Calculus of Variations*.
- [7] S. Müller. Variational models for microstructure and phase transitions. In *Calculus of variations and geometric evolution problems (Cetraro, 1996)*, pages 85–210, 1999.
- [8] S. Müller and Šverák. Convex integration for Lipschitz mappings and counterexamples to regularity. *Ann. of Math.*, 157(3):715–742, 2003.
- [9] V. Nesi, M. Palombaro, and M. Ponsiglione. Gradient integrability and rigidity results for two-phase conductivities in two dimensions. *Ann. Inst. H. Poincaré Anal. Non Linéaire*, 31(3):615–638, 2014.
- [10] M. Oliva. Bi-Sobolev homeomorphisms f with df and df^1 of low rank using laminates. *Calc. Var. Partial Differential Equations*, 55(6):55–135, 2016.
- [11] P. Pedregal. Laminates and microstructure. *European J. Appl. Math.*, 4(2):121–149, 1993.
- [12] S. Petermichl and A. Volberg. Heating of the Ahlfors-Beurling operator: weakly quasiregular maps on the plane are quasiregular. *Duke Math. J.*, 112:281–305, 2002.

(Silvio Fanzon) UNIVERSITY OF SUSSEX, DEPARTMENT OF MATHEMATICS, PEVENSEY 2 BUILDING, FALMER CAMPUS, BRIGHTON BN1 9QH, UNITED KINGDOM

E-mail address: S.Fanzon@sussex.ac.uk

(Mariapia Palombaro) UNIVERSITY OF SUSSEX, DEPARTMENT OF MATHEMATICS, PEVENSEY 2 BUILDING, FALMER CAMPUS, BRIGHTON BN1 9QH, UNITED KINGDOM

E-mail address: M.Palombaro@sussex.ac.uk