

LINEARIZED PLASTICITY IS THE EVOLUTIONARY Γ -LIMIT OF FINITE PLASTICITY

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ABSTRACT. We provide a rigorous justification of the classical linearization approach in plasticity. By taking the small-deformations limit, we prove via Γ -convergence for rate-independent processes that energetic solutions of the quasi-static finite-strain elastoplasticity system converge to the unique strong solution of linearized elastoplasticity.

1. INTRODUCTION

This paper is devoted to the rigorous justification of the classical linearization approach in finite-strain elastoplasticity. When restricting to the small-deformation realm it is indeed customary to leave the nonlinear finite-strain frame and resort to linearized theories instead. This reduction is usually motivated by means of heuristic Taylor expansion arguments. Here, we aim at complement these formal motivations by providing a rigorous linearization proof by means of an *evolutionary* Γ -convergence analysis of rate-independent processes. In particular, we address the general time-dependent case, which e.g. allows for cyclic loading.

In the stationary framework, the pioneering contribution in this context goes back to DAL MASO, NEGRI, & PERCIVALE [DNP02] who devised a convergence proof of finite-strain elasticity to linearized elasticity. Later, the argument has been refined by AGOSTINIANI, DAL MASO, & DESIMONE [ADD11] and extended to multi-well energies by SCHMIDT [Sch08] and to residually stressed materials by PARONI & TOMASSETTI [PT09, PT11]. The reader is also referred to [GN10, MN11, Neu10] for some related results in the direction of homogenization, to [AD11] for an application to the study of nematic elastomers, to [BSV07, Sch09] in the context of convergence of atomistic models, and to [SZ11] in relation with dislocation theory.

To our knowledge, this is the first result in the *evolutionary* case. With respect to the stationary case of [DNP02], the evolution situation is quite more involved. Indeed, the argument in [DNP02] relies on the Γ -convergence proof of the small-deformation energy functional to its linearization limit. Here, we are instead forced to cope with the occurrence of dissipative plastic evolution by means of a delicate recovery sequence construction relating energy and dissipation. We emphasize

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that finite-strain elastoplasticity is based on the multiplicative decomposition of the strain tensors. Moreover, the plastic tensor is to be considered as an element of a multiplicative matrix group. We have to control these noncommutative *multiplicative* structures in linear function spaces and to establish their convergence to the corresponding *linear* additive structures. In order to give some details in this direction we cannot avoid introducing some minimal notation.

Finite-strain elastoplasticity is usually based on the multiplicative decomposition $\nabla\varphi = F_{\text{el}}F_{\text{pl}}$ [Lee69]. Here $\varphi : \Omega \rightarrow \mathbb{R}^d$ is the deformation of the body with respect to the reference configuration $\Omega \subset \mathbb{R}^d$ ($d = 2, 3$) while F_{el} and $F_{\text{pl}} \in \text{SL}(d)$ stand for the elastic and the plastic strain, respectively. Then, the stored energy in the body is written as

$$\int_{\Omega} W_{\text{el}}(\nabla\varphi F_{\text{pl}}^{-1}) \, dx + \int_{\Omega} W_{\text{h}}(F_{\text{pl}}) \, dx$$

where W_{el} is a frame-indifferent elastic stored-energy density and W_{h} describes hardening. The plastic flow rule is expressed by means of a suitably defined dissipation distance $D : \text{SL}(d) \times \text{SL}(d) \rightarrow [0, \infty]$. In particular $D(F_{\text{pl}}, \widehat{F}_{\text{pl}})$ represents the minimal dissipated energy for an evolution from the plastic strain F_{pl} to \widehat{F}_{pl} and is given via a positively 1-homogeneous dissipation function R by

$$D(F_{\text{pl}}, \widehat{F}_{\text{pl}}) = D(I, \widehat{F}_{\text{pl}}F_{\text{pl}}^{-1}) = \inf \int_{\Omega} \int_0^1 R(\dot{P}P^{-1}) \, dt \, dx,$$

the infimum being taken among all smooth trajectories $P : [0, 1] \rightarrow \mathbb{R}^{d \times d}$ connecting F_{pl} to \widehat{F}_{pl} . Starting from these functionals, by specifying loadings, boundary, and initial conditions, suitably weak solutions of the quasi-static finite-plasticity system (see Section 2) can be defined. We refer to [Mie03] for more information on the mathematical modeling of finite-strain elastoplasticity. There also models with additional hardening variables are given. Here we however refrain from maximal generality in order to emphasize the main features of the limiting process.

Let now the deformation and the plastic strain be small. In particular, for $\varepsilon > 0$ let $\varphi_{\varepsilon} = \text{id} + \varepsilon u$ and $F_{\text{pl}, \varepsilon} = I + \varepsilon z$ where u is interpreted as the displacement and z is the linearized plastic strain. Correspondingly, we have that $F_{\text{el}, \varepsilon} = \nabla\varphi_{\varepsilon}F_{\text{pl}, \varepsilon}^{-1} = (\text{id} + \varepsilon \nabla u)(I + \varepsilon z)^{-1}$ and we are lead to the consideration of the rescaled finite-strain elastoplasticity energy and dissipation functionals

$$\begin{aligned} & \frac{1}{\varepsilon^2} \int_{\Omega} W_{\text{el}}((I + \varepsilon \nabla u)(I + \varepsilon z)^{-1}) \, dx + \frac{1}{\varepsilon^2} \int_{\Omega} W_{\text{h}}(I + \varepsilon z) \, dx, \\ & \frac{1}{\varepsilon} D((I + \varepsilon z), (I + \varepsilon \widehat{z})). \end{aligned}$$

Note that the rescalings above are such that, by assuming W_{el} and W_{h} to admit a quadratic expansion around identity, one can check that

$$\begin{aligned} \frac{1}{\varepsilon^2} \int_{\Omega} W_{\text{el}}((I + \varepsilon \nabla u)(I + \varepsilon z)^{-1}) \, dx & \rightarrow \frac{1}{2} \int_{\Omega} (\nabla u - z) : \mathbb{C}(\nabla u - z) \, dx, \\ \frac{1}{\varepsilon^2} \int_{\Omega} W_{\text{h}}(I + \varepsilon z) \, dx & \rightarrow \frac{1}{2} \int_{\Omega} z : \mathbb{H}z \, dx \\ \frac{1}{\varepsilon} D((I + \varepsilon z), (I + \varepsilon \widehat{z})) & \rightarrow \int_{\Omega} R(\widehat{z} - z) \, dx. \end{aligned}$$

This pointwise convergence is the classical justification of linearization in plasticity. On the other hand, it is not sufficient in itself for proving that finite-strain elastoplasticity trajectories actually converge to a solution of the linearized-plasticity system.

Before going on let us mention that the solution concept which is here under consideration is that of *energetic solutions*. Starting from [MT04], this solution notion has been extensively applied in many different rate-independent contexts. We shall however record that one of the main motivations for introducing energetic solutions was exactly that of targeting existence theories for finite-strain elastoplasticity. In this respect, note that the only available existence result for finite-strain elastoplastic evolution has been recently obtained within the energetic solvability frame in [MM09] after adding the regularizing term $|\nabla F_{\text{pl}}|^r$ for $r > 1$ (see also [MM06] for some preliminary result),

Our result consists in proving the convergence of energetic solutions of the finite-strain elastoplasticity system to linearized-plasticity solutions. In order to prove this convergence we follow the abstract evolutionary Γ -convergence theory for energetic solutions of rate-independent processes developed in [MRS08]. We shall mention that this evolutionary Γ -convergence method has recently attracted attention and has been successfully considered in connection with numerical approximations [KMR05, MR09, GP06a], damage [BRM09, TM10], fracture [GP06b], delamination [RSZ09], dimension reduction [FPZ10, LM11], homogenization [Tim09], and optimal control [Rin08, Rin09].

According to [MRS08], the convergence of the trajectories $(u_\varepsilon, z_\varepsilon)$ follows by proving two *separate* Γ -liminf inequalities for energy and dissipation and constructing of a *mutual recovery sequence* relating both. Note that separate Γ -convergence for energy and dissipation is not sufficient to pass to the limit within rate-independent processes. Apart from the additional technicalities due to the presence of the plastic strain and the dissipation functional, it is the delicate construction of the mutual recovery sequence that distinguishes our argument from all the already developed stationary analyses in the spirit of [DNP02].

2. PROBLEM SETUP AND RESULTS

Let the reference configuration $\Omega \subset \mathbb{R}^d$ be an open, bounded, and connected set with Lipschitz boundary. Moreover, let $\Gamma \subset \partial\Omega$ be relatively open with $\mathcal{H}^{d-1}(\Gamma) > 0$. We define the state space as

$$\mathcal{Q} := \mathcal{U} \times \mathcal{Z} := \{u \in H^1(\Omega; \mathbb{R}^d) \mid u = 0 \text{ on } \Gamma\} \times L^2(\Omega; \mathbb{R}^{d \times d}).$$

Note that the choice of the homogeneous Dirichlet condition on the displacement u is just motivated by the sake of simplicity. In particular, different boundary conditions may be considered as well.

For all given $A \in \mathbb{R}^{d \times d}$ we denote its symmetric and antisymmetric parts as $A^{\text{sym}} := (A + A^\top)/2$ and $A^{\text{anti}} = A - A^{\text{sym}}$. We indicate by $\mathbb{R}_{\text{sym}}^{d \times d}$ and $\mathbb{R}_{\text{anti}}^{d \times d}$ the subspaces of symmetric and antisymmetric tensors, respectively, whereas $\mathbb{R}_{\text{dev}}^{d \times d}$ stands for the subspace of symmetric and trace-free tensors, also called *deviatoric* tensors. The standard Euclidian tensor norm is denoted by $|\cdot|$ and, for all $A \in \mathbb{R}^{d \times d}$ and

$\tau > 0$, $B_\tau(A)$ indicates the ball $B_\tau(A) := \{B \in \mathbb{R}^{d \times d} \mid |A - B| < \tau\}$. Moreover, the symbol $|\cdot|_{\mathbb{T}}$ stands for the seminorm

$$|A|_{\mathbb{T}}^2 := \frac{1}{2} A : \mathbb{T} A$$

where the 4-tensor $\mathbb{T} \in \mathbb{R}^{d \times d \times d \times d}$ is symmetric ($\mathbb{T}_{ijkl} = \mathbb{T}_{klij}$) and positive semi-definite. For finite-strain elastoplasticity we use the classical notations

$$\begin{aligned} \text{SL}(d) &:= \{P \in \mathbb{R}^{d \times d} \mid \det P = 1\}, \\ \text{SO}(d) &:= \{R \in \text{SL}(d) \mid R^\top R = RR^\top = I\}, \\ \text{GL}_+(d) &:= \{Q \in \mathbb{R}^{d \times d} \mid \det Q > 0\}. \end{aligned}$$

We assume that the elastic energy density functional W_{el} fulfills

$$W_{\text{el}} : \mathbb{R}^{d \times d} \rightarrow [0, \infty], \quad W_{\text{el}} \in C^1(\text{GL}_+(d)), \quad W_{\text{el}} \equiv \infty \text{ on } \mathbb{R}^{d \times d} \setminus \text{GL}_+(d), \quad (2.1a)$$

$$\forall F \in \text{GL}_+(d) \quad \forall R \in \text{SO}(d) : W_{\text{el}}(RF) = W_{\text{el}}(F), \quad (2.1b)$$

$$\forall F \in \text{GL}_+(d) : W_{\text{el}}(F) \geq c_1 \text{dist}^2(F, \text{SO}(d)), \quad (2.1c)$$

$$\forall F \in \text{GL}_+(d) : |F^\top \partial_F W_{\text{el}}(F)| \leq c_2(W_{\text{el}}(F) + c_3), \quad (2.1d)$$

$$\exists \mathbb{C} \geq 0 \quad \forall \delta > 0 \quad \exists c_{\text{el}}(\delta) > 0 \quad \forall A \in B_{c_{\text{el}}(\delta)}(0) : |W_{\text{el}}(I+A) - |A|_{\mathbb{C}}^2| \leq \delta |A|_{\mathbb{C}}^2, \quad (2.1e)$$

for some positive c_1, c_2 . Assumption (2.1b) is nothing but frame indifference and the nondegeneracy requirement (2.1c) is quite classical. Assumption (2.1d) entails the controllability of the *Mandel tensor* $F^\top \partial_F W_{\text{el}}(F)$ by means of the energy. This is a crucial condition in finite-strain elastoplasticity (cf. [Bal84b, Bal02]) and was used in the context of rate-independent processes in [FM06, MM09]. Condition, (2.1e) encodes the local quadratic character of W_{el} around identity. More precisely, (2.1e) states that $|\cdot|_{\mathbb{C}}$ is the second order Taylor expansion of W_{el} at I , and may be reformulated by saying that $A \mapsto W_{\text{el}}(I+A)$ is locally restrained between two multiples of $|\cdot|_{\mathbb{C}}^2$, namely,

$$\forall \delta > 0 \quad \forall A \in B_{c_{\text{el}}(\delta)}(0) : (1-\delta)|A|_{\mathbb{C}}^2 \leq W_{\text{el}}(I+A) \leq (1+\delta)|A|_{\mathbb{C}}^2.$$

Moreover, (2.1e) entails

$$W_{\text{el}}(I) = 0, \quad \partial_F W_{\text{el}}(I) = 0, \quad \partial_F^2 W_{\text{el}}(I) = \mathbb{C}, \quad (2.2)$$

which, in particular, yields that the reference state is stress free. On the other hand, by assuming (2.2) and letting $W_{\text{el}} \in C^2$ in neighborhood of I , relation (2.1e) follows.

Note that the symmetry of the elastic tensor \mathbb{C} (implicitly assumed in the notation $|\cdot|_{\mathbb{C}}$) may be directly obtained from the last of (2.2) by assuming additional smoothness on W_{el} . Moreover, letting $A \in \mathbb{R}^{d \times d}$ be given, as we have that $\exp(A^{\text{anti}}) \in \text{SO}(d)$, the frame indifference (2.1b) entails that the function $t \mapsto \partial_F W_{\text{el}}(\exp(tA^{\text{anti}}))$ is constantly equal to $\partial_F W_{\text{el}}(I) = 0$. Hence, by taking its derivative with respect to t and evaluating it at $t = 0$ we get $\mathbb{C}A^{\text{anti}} = 0$. Namely, \mathbb{C} necessarily fulfills also the so called *minor symmetries* $\mathbb{C}_{ijkl} = \mathbb{C}_{jikl} = \mathbb{C}_{ijlk}$ and we have

$$\forall A \in \mathbb{R}^{d \times d} : \mathbb{C}A = \mathbb{C}A^{\text{sym}}. \quad (2.3)$$

On the other hand, as effect of the nondegeneracy (2.1c) and assumption (2.1e) we have that \mathbb{C} is positive definite on $\mathbb{R}_{\text{sym}}^{d \times d}$. Indeed, by linearizing $d(\cdot, \text{SO}(d))$

around identity we have [FJM02, (3.21)]

$$\forall B \in \mathbb{R}^{d \times d} : \quad d(B, \text{SO}(d)) = |B^{\text{sym}} - I| + O(|B - I|^2). \quad (2.4)$$

Hence, given $A \in \mathbb{R}^{d \times d}$ and $\eta, \delta > 0$, by choosing $B = I + \eta A$ in the latter we have

$$\begin{aligned} c_1 |A^{\text{sym}}|^2 &\stackrel{(2.4)}{=} \lim_{\eta \rightarrow 0} \frac{c_1}{\eta^2} d^2(I + \eta A, \text{SO}(d)) \\ &\stackrel{(2.1c)}{\leq} \lim_{\eta \rightarrow 0} \frac{1}{\eta^2} W_{\text{el}}(I + \eta A) \stackrel{(2.1e)}{\leq} (1 + \delta) |A|_{\mathbb{C}}^2 \end{aligned}$$

so that, by taking $\delta \rightarrow 0$, we have

$$\forall A \in \mathbb{R}^{d \times d} : \quad c_1 |A^{\text{sym}}|^2 \leq |A|_{\mathbb{C}}^2 = |A^{\text{sym}}|_{\mathbb{C}}^2. \quad (2.5)$$

Note that all assumptions (2.1a)-(2.1e) are consistent with the usual polyconvexity framework

$$\begin{aligned} F &\mapsto W_{\text{el}}(F) \quad \text{polyconvex,} \\ W_{\text{el}}(F) &\rightarrow \infty \quad \text{for } \det F \rightarrow 0. \end{aligned}$$

Our assumptions on the hardening functional $W_h : \mathbb{R}^{d \times d} \rightarrow [0, \infty]$ read

$$W_h(P) := \begin{cases} \widetilde{W}_h(P) & \text{if } P \in K, \\ \infty & \text{if } P \in \mathbb{R}^{d \times d} \setminus K, \end{cases} \quad (2.6a)$$

where K is compact in $\text{SL}(d)$ and contains a neighborhood of I , (2.6b)

$\widetilde{W}_h : \mathbb{R}^{d \times d} \rightarrow \mathbb{R}$ is locally Lipschitz continuous and (2.6c)

$$\exists \mathbb{H} \geq 0 \quad \forall \delta > 0 \quad \exists c_h(\delta) > 0 \quad \forall A \in B_{c_h(\delta)}(0) : \quad |\widetilde{W}_h(I + A) - |A|_{\mathbb{H}}^2| \leq \delta |A|_{\mathbb{H}}^2, \quad (2.6d)$$

$$\exists c_3 > 0 \quad \forall A \in \mathbb{R}^{d \times d} : \quad W_h(I + A) \geq c_3 |A|^2. \quad (2.6e)$$

Note that by assumption (2.6b) we can find a constant $c_K > 0$ such that

$$P \in K \quad \Rightarrow \quad |P| + |P^{-1}| \leq c_K, \quad (2.7)$$

$$P \in \text{SL}(d) \setminus K \quad \Rightarrow \quad |P - I| \geq \frac{1}{c_K}. \quad (2.8)$$

The rather strong technical assumption on W_h that its effective domain $K = \{P \in \text{SL}(d) \mid W_h(P) < \infty\}$ fulfills (2.7) is crucial as it will provide L^∞ -bounds that are essential in order to control the multiplicative terms $(I + \varepsilon \nabla u)(I + \varepsilon z)^{-1}$. Moreover, by combining (2.6d) and (2.6e) we check that

$$\forall A \in \mathbb{R}^{d \times d} : \quad c_3 |A|^2 \leq |A|_{\mathbb{H}}^2. \quad (2.9)$$

As for the dissipation we assume that

$$R^{\text{dev}} : \mathbb{R}_{\text{dev}}^{d \times d} \rightarrow [0, \infty) \quad \text{convex and positively 1-homogeneous,} \quad (2.10a)$$

$$\forall P \in \mathbb{R}_{\text{dev}}^{d \times d} : \quad c_4 |P| \leq R^{\text{dev}}(P) \leq c_5 |P|, \quad (2.10b)$$

$$R : \mathbb{R}^{d \times d} \rightarrow [0, \infty]; \quad R(z) := \begin{cases} R^{\text{dev}}(z) & \text{if } z \in \mathbb{R}_{\text{dev}}^{d \times d}, \\ \infty & \text{else,} \end{cases} \quad (2.10c)$$

for positive c_4, c_5 . Moreover, we define

$$D : \mathbb{R}^{d \times d} \times \mathbb{R}^{d \times d} \rightarrow [0, \infty], \quad \text{with } D(P, \hat{P}) = D(I, \hat{P}P^{-1}) \quad \text{given by}$$

$$D(I, \hat{P}) := \inf \left\{ \int_0^1 R(\dot{P}P^{-1}) dt \mid \right.$$

$$\left. P \in C^1(0, 1; \mathbb{R}^{d \times d}), P(0) = I, P(1) = \hat{P} \right\}. \quad (2.11)$$

If P is not invertible, we set $D(P, \hat{P}) = \infty$. Note in particular that $D(I, P) < \infty$ implies $\det P = 1$. Moreover, there exists $c_6 > 0$ such that

$$\forall P, Q \in K \subset \text{SL}(d) : D(P, Q) \leq c_6, \quad D(I, P) \leq c_6 |P - I|. \quad (2.12)$$

For the first estimate the continuity of D and the compactness of K is sufficient. For the second, we need to establish the estimate only for P close to I , where it follows from $D(I, P) \leq R^{\text{dev}}(\log P) \leq c_5 |\log P| \leq c_6 |P - I|$, since the matrix logarithm is well-defined and Lipschitz continuous in a neighborhood of I . See also [MM09, Ex. 3.2] and the references given there for global bounds on D .

The quasistatic evolution of the finite-strain and linearized elastoplasticity systems are driven by the energy functionals $\mathcal{W}_\varepsilon, \mathcal{W}_0 : \mathcal{Q} \rightarrow (-\infty, \infty]$ given by

$$\mathcal{W}_\varepsilon(u, z) := \frac{1}{\varepsilon^2} \int_\Omega W_{\text{el}}((I + \varepsilon \nabla u)(I + \varepsilon z)^{-1}) dx + \frac{1}{\varepsilon^2} \int_\Omega W_{\text{h}}(I + \varepsilon z) dx,$$

$$\mathcal{W}_0(u, z) := \int_\Omega |\nabla u^{\text{sym}} - z^{\text{sym}}|_{\mathbb{C}}^2 dx + \int_\Omega |z|_{\mathbb{H}}^2 dx.$$

Note that, if the second integral in the definition of $\mathcal{W}_\varepsilon(u, z)$ is finite, then $I + \varepsilon z \in K$ almost everywhere by (2.6a). Hence, the inverse $(I + \varepsilon z)^{-1}$ exists and the first integral is well defined.

We prescribe the generalized loading as

$$\ell \in W^{1,1}(0, T; \mathcal{U}') \quad (2.13)$$

and, by letting $\ell_\varepsilon := \varepsilon \ell$, we introduce some notation for the total energy functionals $\mathcal{E}_\varepsilon, \mathcal{E}_0 : [0, T] \times \mathcal{Q} \rightarrow (-\infty, \infty]$ as

$$\mathcal{E}_\varepsilon(t, u, z) := \mathcal{W}_\varepsilon(u, z) - \frac{1}{\varepsilon} \langle \ell_\varepsilon(t), u \rangle = \mathcal{W}_\varepsilon(u, z) - \langle \ell(t), u \rangle$$

$$\mathcal{E}_0(t, u, z) := \mathcal{W}_0(u, z) - \langle \ell(t), u \rangle,$$

Eventually, the dissipative character of the evolution is encoded into the dissipation functions $D_\varepsilon, D_0 : \mathbb{R}^{d \times d} \times \mathbb{R}^{d \times d} \rightarrow [0, \infty]$ and functionals $\mathcal{D}_\varepsilon, \mathcal{D}_0 : (L^1(\Omega; \mathbb{R}^{d \times d}))^2 \rightarrow [0, \infty]$ given by

$$D_\varepsilon(z_1, z_2) := \frac{1}{\varepsilon} D(I + \varepsilon z_1, I + \varepsilon z_2), \quad D_0(z_1, z_2) := R(z_2 - z_1),$$

$$\mathcal{D}_\varepsilon(z_1, z_2) := \int_\Omega D_\varepsilon(z_1, z_2) dx, \quad \mathcal{D}_0(z_1, z_2) := \int_\Omega D_0(z_1, z_2) dx.$$

The total dissipation of the process over the time interval $[0, t] \subset [0, T]$ will be given by

$$\text{Diss}_{\mathcal{D}_\varepsilon}(z; [0, t]) := \sup \left\{ \sum_{i=1}^N \mathcal{D}_\varepsilon(z(t^i), z(t^{i-1})) \mid \{0 = t^0 < \dots < t^N = t\} \right\}$$

where the sup is taken over all partitions of $[0, t]$.

From here on, we term *Rate-Independent System* (RIS) the triple $(\mathcal{Q}, \mathcal{E}_\varepsilon, \mathcal{D}_\varepsilon)$ given by the choice of the state space \mathcal{Q} and the energy and dissipation functionals \mathcal{E}_ε and \mathcal{D}_ε . The term *evolutionary Γ -convergence* refers to a suitable notion of convergence for rate-independent systems in the spirit of [MRS08] which in particular entails the convergence of the respective energetic solutions.

A crucial structure in the energetic formulation of RIS is the set $\mathcal{S}_\varepsilon(t)$ of *stable states* at time $t \in [0, T]$, which is defined via

$$\begin{aligned} \mathcal{S}_\varepsilon(t) := \left\{ (u, z) \in \mathcal{Q} \mid \mathcal{E}_\varepsilon(t, u, z) < \infty \text{ and} \right. \\ \left. \mathcal{E}_\varepsilon(t, u, z) \leq \mathcal{E}_\varepsilon(t, \hat{u}, \hat{z}) + \mathcal{D}_\varepsilon(z, \hat{z}) \quad \forall (\hat{u}, \hat{z}) \in \mathcal{Q} \right\}. \end{aligned}$$

Our assumption on the initial data reads

$$\begin{aligned} \mathcal{S}_\varepsilon(0) \ni (u_\varepsilon^0, z_\varepsilon^0) \rightarrow (u_0^0, z_0^0) \text{ weakly in } \mathcal{Q}, \quad z_0^0 \in L^2(\Omega; \mathbb{R}_{\text{dev}}^{d \times d}), \\ \mathcal{E}_\varepsilon(0, u_\varepsilon^0, z_\varepsilon^0) \rightarrow \mathcal{E}_0(0, u_0^0, z_0^0). \end{aligned} \quad (2.14)$$

Note that the latter assumption is not empty as it is fulfilled at least by the natural choice $(u_0, z_0) = (0, 0)$ if $\ell(0) = 0$.

Definition 2.1 (Energetic solutions). *Let $\varepsilon \geq 0$. We say that a trajectory $q_\varepsilon : [0, T] \rightarrow (u_\varepsilon, z_\varepsilon) \in \mathcal{Q}$ is an energetic solution (related to the RIS $(\mathcal{Q}, \mathcal{E}_\varepsilon, \mathcal{D}_\varepsilon)$) if $(u_\varepsilon(0), z_\varepsilon(0)) = (u_\varepsilon^0, z_\varepsilon^0)$, the map $t \mapsto \langle \dot{\ell}, u_\varepsilon \rangle$ is integrable, and, for all $t \in [0, T]$,*

$$(u_\varepsilon(t), z_\varepsilon(t)) \in \mathcal{S}_\varepsilon(t), \quad (2.15)$$

$$\mathcal{E}_\varepsilon(t, u_\varepsilon(t), z_\varepsilon(t)) + \text{Diss}_{\mathcal{D}_\varepsilon}(z_\varepsilon; [0, t]) = \mathcal{E}_\varepsilon(0, u_\varepsilon^0, z_\varepsilon^0) - \int_0^t \langle \dot{\ell}, u_\varepsilon \rangle \, ds. \quad (2.16)$$

An energetic solution will be called a finite-plasticity solution if $\varepsilon > 0$ and a linearized-plasticity solution for $\varepsilon = 0$.

Note that linearized-plasticity solutions (u_0, z_0) are unique as effect of the quadratic and uniformly convex character of \mathcal{W}_0 . Moreover, from assumption (2.13) we get that $(u_0, z_0) \in W^{1,1}(0, T; \mathcal{Q})$ and

$$\forall t \in [0, T] : \text{Diss}_{\mathcal{D}_0}(z_0; [0, t]) = \int_0^t R(\dot{z}_0) \, ds.$$

The reader is referred to [Hil50, Lub90, Mar75] for some general introduction to plasticity and to [HR99, Joh76, Suq81] for the classical well-posedness theory for linearized elastoplasticity.

Our main result reads as follows and will be proved in Section 3 as a special instance of the general theory of [MRS08].

Theorem 2.2 (Finite plasticity Γ -converges to linearized plasticity). *Assume (2.1)-(2.6), (2.10), and (2.13)-(2.14). Let $(u_\varepsilon, z_\varepsilon)$ be a finite-plasticity solution. Then, $(u_\varepsilon(t), z_\varepsilon(t)) \rightarrow (u_0(t), z_0(t))$ weakly in \mathcal{Q} for all $t \in [0, T]$ where (u_0, z_0) is the unique linearized-plasticity solution.*

Theorem 2.2 is exclusively a convergence result. In particular, we *assume* that finite-plasticity solutions exist. Note however that the existence of finite-plasticity solutions is presently not known within our minimal assumption frame. A possibility here would be that of considering directly some more regular situations including extra compactifying terms like $|\nabla F_{\text{pl}}|^r$ ($r > 1$) such that finite-plasticity solutions exist [MM09]. We shall not follow this line here but rather present a second result based on *approximate minimizers* of the related incremental problems. Indeed, given the time partitions $\{0 = t_\varepsilon^i < \dots < t_\varepsilon^{N_\varepsilon} = T\}$ with diameters $\tau_\varepsilon := \max_{i=1, \dots, N_\varepsilon} (t_\varepsilon^i - t_\varepsilon^{i-1}) \rightarrow 0$ as $\varepsilon \rightarrow 0$, the (iterative) incremental problem

$$(u_\varepsilon^i, z_\varepsilon^i) \in \underset{(u,v) \in \mathcal{Q}}{\text{Arg min}} (\mathcal{E}_\varepsilon(t_\varepsilon^i, u, z) + \mathcal{D}_\varepsilon(z_\varepsilon^{i-1}, z)) \quad \text{for } i = 1, \dots, N_\varepsilon$$

may not be solvable (cf. [CHM02], still see [Mie04, MM06] for some additional discussion). Hence, following [MRS08, Sec. 4] we fix a sequence $0 < \alpha_\varepsilon \rightarrow 0$ in order to control the tolerances for the minimizations and consider the following *approximate incremental problem*

$$\begin{aligned} &\text{Find iteratively } (u_\varepsilon^i, z_\varepsilon^i) \in \mathcal{Q} \text{ such that} \\ &\mathcal{E}_\varepsilon(t_\varepsilon^i, u_\varepsilon^i, z_\varepsilon^i) + \mathcal{D}_\varepsilon(z_\varepsilon^{i-1}, z_\varepsilon^i) \\ &\leq (t_\varepsilon^i - t_\varepsilon^{i-1})\alpha_\varepsilon + \inf_{(u,v) \in \mathcal{Q}} (\mathcal{E}_\varepsilon(t_\varepsilon^i, u, z) + \mathcal{D}_\varepsilon(z_\varepsilon^{i-1}, z)). \end{aligned} \quad (2.17)$$

By the definition of infimum the latter always admits solutions and we will show the following convergence result.

Theorem 2.3 (Convergence of approximate incremental minimizers). *Under the assumptions of Theorem 2.2 let $(u_\varepsilon^i, z_\varepsilon^i)$ be approximate incremental minimizers and $(\bar{u}_\varepsilon, \bar{z}_\varepsilon)$ be the corresponding right-continuous, piecewise-constant interpolants on the time partitions. Then, $(\bar{u}_\varepsilon(t), \bar{z}_\varepsilon(t)) \rightarrow (u_0(t), z_0(t))$ weakly in \mathcal{Q} for all $t \in [0, T]$ where (u_0, z_0) is the unique linearized-plasticity solution.*

In the finite-elasticity case (stationary), using ideas from [DNP02] the convergence of approximate minimizers has been considered in [PT09].

3. PROOFS

The argument basically follows the lines of the abstract analysis of [MRS08]. Still, our setting cannot be completely recovered from the application of the above-mentioned abstract theory as extra care is needed for the treatment of the multiplicative nonlinearities. We hence resort in providing here an independent proof. After establishing the coercivity of the energy in Subsection 3.1, the proof strategy relies in providing *two separate* Γ -liminf inequalities for \mathcal{E}_ε and \mathcal{D}_ε and a *mutual recovery sequence* argument relating both. This is done in Subsections 3.2 and 3.3 below. Eventually, the proofs of Theorems 2.2 and 2.3 are outlined in Subsections 3.4 and 3.5, respectively.

A caveat on notation: henceforth the symbol c stands for any positive constant independent of ε and δ but possibly depending on the fixed data. In particular,

note that c may change from line to line. Moreover, in the following we use the short-hand notation, for all $A \in \mathbb{R}^{d \times d}$,

$$W_{\text{el}}^\varepsilon(A) := \frac{1}{\varepsilon^2} W_{\text{el}}(I + \varepsilon A), \quad W_{\text{h}}^\varepsilon(A) := \frac{1}{\varepsilon^2} W_{\text{h}}(I + \varepsilon A), \quad \widetilde{W}_{\text{h}}^\varepsilon(A) := \frac{1}{\varepsilon^2} \widetilde{W}_{\text{h}}(I + \varepsilon A).$$

3.1. Energy coercivity. We start by providing a uniform coercivity result for the energy. It follows the ideas in [DNP02] and relies on the Rigidity Lemma [FJM02, Thm. 3.1].

Lemma 3.1 (Coercivity). *There exists $c > 0$ such that, for all $(u, z) \in \mathcal{Q}$*

$$\|\nabla u\|_{L^2}^2 + \|z\|_{L^2}^2 + \|\varepsilon z\|_{L^\infty}^2 \leq c(1 + \mathcal{W}_\varepsilon(u, z)). \quad (3.1)$$

Proof. Let us assume with no loss of generality that $\mathcal{W}_\varepsilon(u, z) < \infty$, so that $I + \varepsilon z \in K$ almost everywhere by assumption (2.6a). Hence, $|I + \varepsilon z| \leq c_K$ almost everywhere from property (2.7) and the inverse $(I + \varepsilon z)^{-1}$ exists almost everywhere. Thus, we have that $\|\varepsilon z\|_{L^\infty} \leq c$. Moreover, one readily checks from the coercivity (2.6e) that

$$c_3 \|z\|_{L^2}^2 \leq \int_{\Omega} W_{\text{h}}^\varepsilon(z) \, dx \leq \mathcal{W}_\varepsilon(u, z). \quad (3.2)$$

For the displacement u we follow ideas from [DNP02]. Given any $Q \in \text{SO}(d)$ by letting $\varphi = \text{id} + \varepsilon u$ and $F_{\text{el}} = \nabla \varphi (I + \varepsilon z)^{-1}$ we have

$$\begin{aligned} |\nabla \varphi - Q|^2 &= |\nabla \varphi - Q(I + \varepsilon z) + \varepsilon Q z|^2 = |(F_{\text{el}} - Q)(I + \varepsilon z) + \varepsilon Q z|^2 \\ &\leq c(|F_{\text{el}} - Q|^2 |I + \varepsilon z|^2 + \varepsilon^2 |z|^2) \leq c(|F_{\text{el}} - Q|^2 + \varepsilon^2 |z|^2). \end{aligned}$$

In particular, by passing to the infimum for $Q \in \text{SO}(d)$ we have checked that

$$\text{dist}^2(\nabla \varphi, \text{SO}(d)) \leq c(\text{dist}^2(F_{\text{el}}, \text{SO}(d)) + \varepsilon^2 |z|^2).$$

By taking the integral in space and using the nondegeneracy condition (2.1c) we obtain that

$$\begin{aligned} \int_{\Omega} \text{dist}^2(\nabla \varphi, \text{SO}(d)) \, dx &\leq c \int_{\Omega} \text{dist}^2(F_{\text{el}}, \text{SO}(d)) \, dx + c\varepsilon^2 \int_{\Omega} |z|^2 \, dx \\ &\stackrel{(3.2)}{\leq} \varepsilon^2 c \mathcal{W}_\varepsilon(u, z). \end{aligned}$$

Hence, the Rigidity Lemma [FJM02, Thm. 3.1] ensures that

$$\|\nabla \varphi - \widehat{Q}\|_{L^2}^2 \leq \varepsilon^2 c \mathcal{W}_\varepsilon(u, z)$$

for some constant rotation $\widehat{Q} \in \text{SO}(d)$. Finally, using [DNP02, Prop. 3.4] and $\varphi|_{\Gamma} = \text{id}$ as $u \in \mathcal{U}$, we conclude $|\widehat{Q} - I|^2 \leq \varepsilon^2 c \mathcal{W}_\varepsilon(u, z)$. Then, we have

$$\|\nabla u\|_{L^2}^2 = \frac{1}{\varepsilon^2} \|\nabla \varphi - I\|_{L^2}^2 \leq \frac{2}{\varepsilon^2} \|\nabla \varphi - \widehat{Q}\|_{L^2}^2 + \frac{2}{\varepsilon^2} \|\widehat{Q} - I\|_{L^2}^2 \leq c \mathcal{W}_\varepsilon(u, z)$$

and the bound (3.1) follows. \square

3.2. Γ -liminf inequalities. Next, we turn our attention to the proof of the separate Γ -liminf inequalities for energy and dissipation. Let us start with a statement concerning the energy densities.

Lemma 3.2. *Under assumptions (2.1e) and (2.6d), we have*

$$W_{\text{el}}^\varepsilon \rightarrow |\cdot|_{\mathbb{C}}^2 \quad \text{and} \quad \widetilde{W}_{\text{h}}^\varepsilon \rightarrow |\cdot|_{\mathbb{H}}^2 \quad \text{locally uniformly.} \quad (3.3)$$

Moreover, we have

$$|z|_{\mathbb{H}}^2 \leq \inf \left\{ \liminf_{\varepsilon \rightarrow 0} W_{\text{h}}^\varepsilon(z_\varepsilon) \mid z_\varepsilon \rightarrow z \right\}. \quad (3.4)$$

Proof. Let $K_0 \in \mathbb{R}^{d \times d}$, fix $\delta > 0$ and find the corresponding $c_{\text{el}}(\delta) > 0$ from condition (2.1e). As $\varepsilon K_0 \subset B_{c_{\text{el}}(\delta)}(0)$ for ε sufficiently small we have that

$$\limsup_{\varepsilon \rightarrow 0} \sup_{K_0} |W_{\text{el}}^\varepsilon - |\cdot|_{\mathbb{C}}^2| \leq \delta \sup_{K_0} |\cdot|^2 \leq \delta c$$

and local uniform convergence follows from $\delta > 0$ being arbitrary. The same argument applies to $\widetilde{W}_{\text{h}}^\varepsilon$.

As for the Γ -liminf inequality (3.4), let $z_\varepsilon \rightarrow z$ and assume with no loss of generality that $\sup_\varepsilon W_{\text{h}}^\varepsilon(z_\varepsilon) < \infty$. Hence, $W_{\text{h}}^\varepsilon(z_\varepsilon) = \widetilde{W}_{\text{h}}^\varepsilon(z_\varepsilon)$ and the inequality follows from the above proved uniform convergence. \square

We are now in the position of proving the Γ -liminf estimate for the energy. It follows indeed from (3.3) and the lower-semicontinuity result of Lemma 4.2.

Lemma 3.3 (Γ -liminf for the energy). *For all $(u, z) \in \mathcal{Q}$ we have*

$$\mathcal{W}_0(u, z) \leq \inf \left\{ \liminf_{\varepsilon \rightarrow 0} \mathcal{W}_\varepsilon(u_\varepsilon, z_\varepsilon) \mid (u_\varepsilon, z_\varepsilon) \rightarrow (u, z) \text{ weakly in } \mathcal{Q} \right\}.$$

Proof. Let $(u_\varepsilon, z_\varepsilon) \rightarrow (u, z)$ weakly in \mathcal{Q} . We can assume with no loss of generality that $\sup_\varepsilon \mathcal{W}_\varepsilon(u_\varepsilon, z_\varepsilon) < \infty$. Owing to the Γ -liminf inequality (3.4) and the lower semicontinuity Lemma 4.2 we readily conclude that

$$\int_{\Omega} |z|_{\mathbb{H}}^2 \leq \liminf_{\varepsilon \rightarrow 0} \int_{\Omega} W_{\text{h}}^\varepsilon(z_\varepsilon) \, dx = \liminf_{\varepsilon \rightarrow 0} \frac{1}{\varepsilon^2} \int_{\Omega} W_{\text{h}}(I + \varepsilon z_\varepsilon) \, dx. \quad (3.5)$$

Moreover, $\mathcal{W}_\varepsilon(u_\varepsilon, z_\varepsilon) < \infty$ implies $\varepsilon z_\varepsilon \in K - I$ almost everywhere. In particular, $\varepsilon z_\varepsilon$ are bounded in L^∞ . The same holds for $(I + \varepsilon z_\varepsilon)^{-1}$ as

$$(I + \varepsilon z_\varepsilon)^{-1} = \text{cof}(I + \varepsilon z_\varepsilon) / \det(I + \varepsilon z_\varepsilon) = \text{cof}(I + \varepsilon z_\varepsilon).$$

We define the auxiliary tensors

$$w_\varepsilon := \frac{1}{\varepsilon} \left((I + \varepsilon z_\varepsilon)^{-1} - I + \varepsilon z_\varepsilon \right) = \varepsilon (I + \varepsilon z_\varepsilon)^{-1} z_\varepsilon^2, \quad (3.6)$$

so that $(I + \varepsilon z_\varepsilon)^{-1} = I - \varepsilon z_\varepsilon + \varepsilon w_\varepsilon$. By the first equality in (3.6) we have $\|\varepsilon w_\varepsilon\|_{L^\infty} \leq c$, while the second gives

$$\|w_\varepsilon\|_{L^1} = \|(I + \varepsilon z_\varepsilon)^{-1} z_\varepsilon^2\|_{L^1} \leq c \varepsilon \|z_\varepsilon\|_{L^2}^2 \leq c \varepsilon$$

where we have also used the boundedness in L^2 of z_ε from (3.1). Thus, by interpolation, w_ε is bounded in L^2 as well, so that $w_\varepsilon \rightarrow 0$ weakly in L^2 .

Given $A_\varepsilon := (F_{\text{el},\varepsilon} - I)/\varepsilon$ we want to show the weak L^2 convergence $A_\varepsilon \rightharpoonup \nabla u - z$. From

$$A_\varepsilon = \frac{1}{\varepsilon} ((I + \varepsilon \nabla u_\varepsilon)(I + \varepsilon z_\varepsilon)^{-1} - I) \quad (3.7)$$

we find $I + \varepsilon A_\varepsilon = (I + \varepsilon \nabla u_\varepsilon)(I + \varepsilon z_\varepsilon)^{-1}$ and compute that

$$A_\varepsilon = \frac{1}{\varepsilon} ((I + \varepsilon \nabla u_\varepsilon)(I - \varepsilon z_\varepsilon + \varepsilon w_\varepsilon) - I) = \nabla u_\varepsilon - z_\varepsilon + w_\varepsilon - \varepsilon (\nabla u_\varepsilon z_\varepsilon - \nabla u_\varepsilon w_\varepsilon).$$

Hence, as we have that $\nabla u_\varepsilon - z_\varepsilon \rightharpoonup \nabla u - z$ and $w_\varepsilon \rightarrow 0$ weakly in L^2 , we have to show $v_\varepsilon := \nabla u_\varepsilon (\varepsilon z_\varepsilon - \varepsilon w_\varepsilon) \rightarrow 0$ weakly in L^2 as well. Indeed, the boundedness in L^2 of v_ε follows from $\|\nabla u_\varepsilon\|_{L^2} \leq c$ (see (3.1)) and the L^∞ -boundedness of $\varepsilon z_\varepsilon$ and $\varepsilon w_\varepsilon$. Moreover, since z_ε and w_ε are bounded in L^2 we have $\|v_\varepsilon\|_{L^1} \leq c\varepsilon$ and conclude $v_\varepsilon \rightarrow 0$ weakly in L^2 .

Eventually, owing to Lemma 3.2, we are in the position of exploiting the lower semicontinuity Lemma 4.2 in order to obtain that

$$\begin{aligned} \int_{\Omega} |\nabla u - z|_{\mathbb{C}}^2 &\leq \liminf_{\varepsilon \rightarrow 0} \int_{\Omega} W_{\text{el}}^\varepsilon(A_\varepsilon) \, dx \\ &= \liminf_{\varepsilon \rightarrow 0} \frac{1}{\varepsilon^2} \int_{\Omega} W_{\text{el}}((I + \varepsilon \nabla u_\varepsilon)(I + \varepsilon z_\varepsilon)^{-1}) \, dx. \end{aligned}$$

Finally, by recalling relation (2.3) and the already established (3.5) the assertion follows. \square

Before moving to the Γ -liminf inequality for the dissipation functionals \mathcal{D}_ε , we prepare here a preliminary result on the functions D_ε .

Lemma 3.4 (Γ -convergence of D_ε). *$D_\varepsilon \rightarrow D_0$ in the sense of Γ -convergence.*

Proof. Γ -liminf inequality. Let $(z_\varepsilon, \widehat{z}_\varepsilon) \rightarrow (z, \widehat{z})$ and assume with no loss of generality that $\sup_\varepsilon D_\varepsilon(z_\varepsilon, \widehat{z}_\varepsilon) < \infty$. In particular, we have that $(I + \varepsilon \widehat{z}_\varepsilon)(I + \varepsilon z_\varepsilon)^{-1} \in \text{SL}(d)$. By defining

$$\zeta_\varepsilon := \frac{1}{\varepsilon} ((I + \varepsilon \widehat{z}_\varepsilon)(I + \varepsilon z_\varepsilon)^{-1} - I) = \widehat{z}_\varepsilon - z_\varepsilon + w_\varepsilon - \varepsilon \widehat{z}_\varepsilon z_\varepsilon + \varepsilon \widehat{z}_\varepsilon w_\varepsilon$$

where w_ε is given in (3.6), we readily check that $I + \varepsilon \zeta_\varepsilon \in \text{SL}(d)$ and $\zeta_\varepsilon \rightarrow \widehat{z} - z$.

Let now $t \mapsto P_\varepsilon(t) \in C^1(0, 1; \mathbb{R}^{d \times d})$ be such that $P_\varepsilon(0) = I$, $P_\varepsilon(1) = I + \varepsilon \zeta_\varepsilon$, and

$$D(I, I + \varepsilon \zeta_\varepsilon) \geq (1 - \varepsilon) \int_0^1 R(\dot{P}_\varepsilon P_\varepsilon^{-1}) \, dt.$$

Such function P_ε exists by the very definition of D . By possibly reparametrizing P_ε and using assumption (2.10b) and bound (2.12) we can assume that

$$c_4 |\dot{P}_\varepsilon(t) P_\varepsilon^{-1}(t)| \stackrel{(2.10b)}{\leq} R(\dot{P}_\varepsilon(t) P_\varepsilon^{-1}(t)) \leq 2D(I, I + \varepsilon \zeta_\varepsilon) \stackrel{(2.12)}{\leq} c\varepsilon. \quad (3.8)$$

Hence,

$$|P_\varepsilon(t) - I| \leq \int_0^t |\dot{P}_\varepsilon P_\varepsilon^{-1}| |P_\varepsilon| \, ds \leq c\varepsilon \int_0^t |P_\varepsilon| \, ds \leq c\varepsilon \left(1 + \int_0^t |P_\varepsilon - I| \, ds \right)$$

so that $P_\varepsilon \rightarrow I$ uniformly by Gronwall Lemma.

By defining $\widehat{P}_\varepsilon(t) = I + (P_\varepsilon(t) - I)/\varepsilon$ one has that $\widehat{P}_\varepsilon(0) = I$ and $\widehat{P}_\varepsilon(1) = I + \zeta_\varepsilon$. Moreover, as $\varepsilon \dot{\widehat{P}}_\varepsilon = \dot{P}_\varepsilon$ and R is positively 1-homogeneous (2.10a), we have that

$$\frac{1}{\varepsilon} D(I, I + \varepsilon \zeta_\varepsilon) \geq (1 - \varepsilon) \int_0^1 R(\dot{\widehat{P}}_\varepsilon P_\varepsilon^{-1}) dt.$$

Owing now to bound (3.8), by possibly extracting not relabeled subsequences, we have that $\dot{\widehat{P}}_\varepsilon \rightarrow Q$ weakly-star in $L^\infty(0, 1; \mathbb{R}^{d \times d})$ and

$$\begin{aligned} \liminf_{\varepsilon \rightarrow 0} D_\varepsilon(z_\varepsilon, \widehat{z}_\varepsilon) &= \liminf_{\varepsilon \rightarrow 0} \frac{1}{\varepsilon} D(I, I + \varepsilon \zeta_\varepsilon) \\ &\geq \liminf_{\varepsilon \rightarrow 0} \int_0^1 R(\dot{\widehat{P}}_\varepsilon P_\varepsilon^{-1}) dt \geq \int_0^1 R(Q) dt \geq R(\tilde{Q}) \end{aligned}$$

where we have exploited the lower semicontinuity tool of Lemma 4.2 and used Jensen's inequality with $\tilde{Q} = \int_0^1 Q dt$.

Finally, by integrating we have that

$$\tilde{Q} = \int_0^1 Q dt = \lim_{\varepsilon \rightarrow 0} \int_0^1 \dot{\widehat{P}}_\varepsilon dt = \lim_{\varepsilon \rightarrow 0} \zeta_\varepsilon = \widehat{z} - z$$

so that we have checked

$$\liminf_{\varepsilon \rightarrow 0} D_\varepsilon(z_\varepsilon, \widehat{z}_\varepsilon) \geq R(\widehat{z} - z).$$

Recovery sequence. Given $\zeta \in \mathbb{R}_{\text{dev}}^{d \times d}$ we have that $\exp(\zeta) \in \text{SL}(d)$ and, by taking $P(t) := \exp(t\zeta)$ into the definition of D , we readily check that $D(I, \exp(\zeta)) \leq R(\zeta)$.

Let now $z, \widehat{z} \in \mathbb{R}_{\text{dev}}^{d \times d}$ be given and define

$$\widehat{z}_\varepsilon = \frac{1}{\varepsilon} (\exp(\varepsilon(\widehat{z} - z))(I + \varepsilon z) - I).$$

As $(I + \varepsilon \widehat{z}_\varepsilon)(I + \varepsilon z)^{-1} = \exp(\varepsilon(\widehat{z} - z))$, we have that

$$\limsup_{\varepsilon \rightarrow 0} D_\varepsilon(z, \widehat{z}_\varepsilon) = \limsup_{\varepsilon \rightarrow 0} \frac{1}{\varepsilon} D(I, \exp(\varepsilon(\widehat{z} - z))) \leq R(\widehat{z} - z) = D_0(z, \widehat{z})$$

so that $(z, \widehat{z}_\varepsilon)$ is a recovery sequence. \square

Owing to Lemma 3.4, it suffices now to apply the lower semicontinuity result in Lemma 4.2 in order to establish the Γ -liminf inequality for the dissipation functionals. More precisely, we have following.

Lemma 3.5 (Γ -liminf for the dissipation).

$$\begin{aligned} \mathcal{D}_0(z, \widehat{z}) &\leq \inf \left\{ \liminf_{\varepsilon \rightarrow 0} \mathcal{D}_\varepsilon(z_\varepsilon, \widehat{z}_\varepsilon) \mid \right. \\ &\quad \left. (z_\varepsilon, \widehat{z}_\varepsilon) \rightarrow (z, \widehat{z}) \text{ weakly in } (L^2(\Omega; \mathbb{R}^{d \times d}))^2 \right\}. \end{aligned} \quad (3.9)$$

3.3. Mutual recovery sequence. We now come to the construction of a *mutual recovery sequence*. Let us recall from [MRS08] that indeed *two separate* Γ -limsup inequalities for energy and dissipation generally do not suffice for passing to the limit in RIS. In particular, the construction of recovery sequences for energy and dissipation has to be *mutually* coordinated.

Lemma 3.6 (Mutual recovery sequence). *Let $t \in [0, T]$, $(u_\varepsilon, z_\varepsilon) \rightarrow (u_0, z_0)$ weakly in \mathcal{Q} , and*

$$\sup_{\varepsilon} \mathcal{E}_\varepsilon(t, u_\varepsilon, z_\varepsilon) < \infty. \quad (3.10)$$

Moreover, let $(\hat{u}_0, \hat{z}_0) := (u_0, z_0) + (\tilde{u}, \tilde{z})$ with $(\tilde{u}, \tilde{z}) \in C_c^\infty(\Omega; \mathbb{R}^d) \times C_c^\infty(\Omega; \mathbb{R}_{\text{dev}}^{d \times d})$. Then, there exist $(\hat{u}_\varepsilon, \hat{z}_\varepsilon) \in \mathcal{Q}$ such that

$$\begin{aligned} & (\hat{u}_\varepsilon, \hat{z}_\varepsilon) \rightarrow (\hat{u}_0, \hat{z}_0) \text{ weakly in } \mathcal{Q} \text{ and} \\ & \limsup_{\varepsilon \rightarrow 0} \left(\mathcal{E}_\varepsilon(t, \hat{u}_\varepsilon, \hat{z}_\varepsilon) - \mathcal{E}_\varepsilon(t, u_\varepsilon, z_\varepsilon) + \mathcal{D}_\varepsilon(z_\varepsilon, \hat{z}_\varepsilon) \right) \\ & \leq \left(\mathcal{E}_0(t, \hat{u}_0, \hat{z}_0) - \mathcal{E}_0(t, u_0, z_0) + \mathcal{D}_0(z_0, \hat{z}_0) \right). \end{aligned} \quad (3.11)$$

Proof. For the sake of clarity, we decompose this argument into subsequent steps. The general strategy of the proof is to choose $(\hat{u}_\varepsilon, \hat{z}_\varepsilon)$ and show convergence to (\hat{u}_0, \hat{z}_0) ,

$$\limsup_{\varepsilon \rightarrow 0} \mathcal{D}_\varepsilon(z_\varepsilon, \hat{z}_\varepsilon) \leq \mathcal{D}_0(z_0, \hat{z}_0) = R(\tilde{z}),$$

and

$$\limsup_{\varepsilon \rightarrow 0} \left(\mathcal{E}_\varepsilon(t, \hat{u}_\varepsilon, \hat{z}_\varepsilon) - \mathcal{E}_\varepsilon(t, u_\varepsilon, z_\varepsilon) \right) \leq \mathcal{E}_0(t, \hat{u}_0, \hat{z}_0) - \mathcal{E}_0(t, u_0, z_0).$$

Note that in order to establish the latter we cannot argue on individual terms but rather aim at exploiting certain cancellations. This resembles the situation of the so-called *quadratic trick* (see, e.g., [MT05]) and crucially uses (2.1d) as well as the smoothness of (\tilde{u}, \tilde{z}) . In particular, note that within this proof the constant c may depend on \tilde{u} and \tilde{z} as well.

Step 1: Choice of the mutual recovery sequence. By defining the functions $\psi_\varepsilon := \text{id} + \varepsilon \tilde{u}$ and $\varphi_\varepsilon := \text{id} + \varepsilon u_\varepsilon$ and the set

$$\Omega_\varepsilon := \{x \in \Omega \mid \exp(\varepsilon \tilde{z}(x))(I + \varepsilon z_\varepsilon(x)) \in K\},$$

the proof of the lemma follows by checking that the choices

$$\begin{aligned} \hat{u}_\varepsilon &:= \frac{1}{\varepsilon} (\psi_\varepsilon \circ \varphi_\varepsilon - \text{id}), \\ \hat{z}_\varepsilon &:= \begin{cases} \frac{1}{\varepsilon} (\exp(\varepsilon \tilde{z})(I + \varepsilon z_\varepsilon) - I) & \text{on } \Omega_\varepsilon \\ z_\varepsilon & \text{else,} \end{cases} \end{aligned}$$

fulfill (3.11) and, in particular, $(\hat{u}_\varepsilon, \hat{z}_\varepsilon) \rightarrow (\hat{u}_0, \hat{z}_0)$ weakly in \mathcal{Q} . The construction of \hat{u}_ε via a composition and of \hat{z}_ε via matrix exponential and multiplication is necessary in order to deal with the multiplicative nature of finite-strain elastoplasticity.

Note that the construction of the mutual recovery sequence is compatible with the constraint $\det(I + \varepsilon \nabla \hat{u}_\varepsilon) > 0$ considered in (2.1a). Indeed, by letting ε be small enough we have that $I + \varepsilon \nabla \tilde{u}$ is everywhere positive definite, hence $\det(I + \varepsilon \nabla \hat{u}) > 0$.

In particular, as $\det(I + \varepsilon \nabla u_\varepsilon) > 0$ almost everywhere by (2.1a) and (3.10), we have that

$$\det(I + \varepsilon \nabla \widehat{u}_\varepsilon) = \det(\nabla \psi_\varepsilon(\varphi_\varepsilon) \nabla \varphi_\varepsilon) = \det(I + \varepsilon \nabla \tilde{u}(\varphi_\varepsilon)) \det(I + \varepsilon \nabla u_\varepsilon) > 0$$

almost everywhere as well. That is, $I + \varepsilon \nabla \widehat{u}_\varepsilon \in \text{GL}_+(d)$ almost everywhere.

From the bound (3.10) we readily have that $I + \varepsilon z_\varepsilon \in \text{SL}(d)$ almost everywhere. Hence, upon noting that

$$I + \varepsilon \widehat{z}_\varepsilon = \begin{cases} \exp(\varepsilon \tilde{z})(I + \varepsilon z_\varepsilon) & \text{on } \Omega_\varepsilon \\ I + \varepsilon z_\varepsilon & \text{else,} \end{cases}$$

we immediately check that $(I + \varepsilon \widehat{z}_\varepsilon) \in K \subset \text{SL}(d)$ almost everywhere and is bounded in L^∞ . Using the fact that $\text{tr } \tilde{z} = 0$ we have $\det \exp(\varepsilon \tilde{z}) = \exp(\varepsilon \text{tr } \tilde{z}) = 1$ and hence $\exp(\varepsilon \tilde{z})(I + \varepsilon z_\varepsilon) \in \text{SL}(d)$ almost everywhere.

Next, note that the measure of the complement of Ω_ε can be controlled by means of a Chebyshev estimate. Indeed, relation (2.8) gives

$$\begin{aligned} |\Omega \setminus \Omega_\varepsilon| &= \int_{\Omega \setminus \Omega_\varepsilon} 1 \, dx \leq c_K^2 \int_{\Omega} |\exp(\varepsilon \tilde{z})(I + \varepsilon z_\varepsilon) - I|^2 \, dx \\ &= c_K^2 \int_{\Omega} |\exp(\varepsilon \tilde{z}) - I + \varepsilon \exp(\varepsilon \tilde{z}) z_\varepsilon|^2 \, dx \leq c\varepsilon^2 \left(1 + \int_{\Omega} z_\varepsilon^2 \, dx \right) \leq c\varepsilon^2. \end{aligned}$$

Now, one has that

$$\begin{aligned} \widehat{z}_\varepsilon - z_\varepsilon &= \frac{1}{\varepsilon} (\exp(\varepsilon \tilde{z})(I + \varepsilon z_\varepsilon) - I) - z_\varepsilon = \frac{1}{\varepsilon} (\exp(\varepsilon \tilde{z}) - I)(I + \varepsilon z_\varepsilon) \quad \text{on } \Omega_\varepsilon, \\ \widehat{z}_\varepsilon - z_\varepsilon &= 0 \quad \text{on } \Omega \setminus \Omega_\varepsilon, \end{aligned}$$

the convergence $|\Omega \setminus \Omega_\varepsilon| \rightarrow 0$, and that \widehat{z}_ε and z_ε are bounded in L^2 . Hence, we readily check that

$$\widehat{z}_\varepsilon - z_\varepsilon \rightarrow \tilde{z} \quad \text{strongly in } L^2(\Omega; \mathbb{R}^{d \times d}). \quad (3.12)$$

This implies that $\widehat{z}_\varepsilon \rightarrow \widehat{z}_0 = z_0 + \tilde{z}$ weakly in L^2 , hence

$$\widehat{z}_\varepsilon + z_\varepsilon \rightarrow \widehat{z}_0 + z_0 \quad \text{weakly in } L^2(\Omega; \mathbb{R}^{d \times d}), \quad (3.13)$$

From the energy bound (3.10) and the coercivity Lemma 3.1 we have that u_ε is bounded in H^1 and $\varepsilon u_\varepsilon \rightarrow 0$ strongly in L^2 . Hence, one has that $\|\varphi_\varepsilon - \text{id}\|_{L^2} = \varepsilon \|u_\varepsilon\|_{L^2} \leq c\varepsilon$ and, by the Lipschitz continuity of $\nabla \tilde{u}$, we conclude that

$$\|\nabla \tilde{u}(\varphi_\varepsilon) - \nabla \tilde{u}\|_{L^2} \leq c \|\varphi_\varepsilon - \text{id}\|_{L^2} = c\varepsilon \|u_\varepsilon\|_{L^2} \leq c\varepsilon. \quad (3.14)$$

Moreover, by computing

$$\begin{aligned} \nabla \widehat{u}_\varepsilon &= \frac{1}{\varepsilon} (\nabla \psi_\varepsilon(\varphi_\varepsilon) \nabla \varphi_\varepsilon - I) = \frac{1}{\varepsilon} ((I + \varepsilon \nabla \tilde{u})(\varphi_\varepsilon) \nabla \varphi_\varepsilon - I) \\ &= \frac{1}{\varepsilon} (\nabla \varphi_\varepsilon + \varepsilon \nabla \tilde{u}(\varphi_\varepsilon) \nabla \varphi_\varepsilon - I) = \nabla u_\varepsilon + \nabla \tilde{u}(\varphi_\varepsilon) + \varepsilon \nabla \tilde{u}(\varphi_\varepsilon) \nabla u_\varepsilon \end{aligned}$$

we obtain that

$$\begin{aligned} \|(\nabla \widehat{u}_\varepsilon - \nabla u_\varepsilon) - \nabla \tilde{u}\|_{L^2} &\leq \|\nabla \tilde{u}(\varphi_\varepsilon) - \nabla \tilde{u}\|_{L^2} + \|\varepsilon \nabla \tilde{u}(\varphi_\varepsilon) \nabla u_\varepsilon\|_{L^2} \\ &\stackrel{(3.14)}{\leq} c\varepsilon + c\varepsilon \|\nabla u_\varepsilon\|_{L^2} \leq c\varepsilon \end{aligned} \quad (3.15)$$

and this implies that $\widehat{u}_\varepsilon \rightarrow \widehat{u}_0 = u_0 + \tilde{u}$ weakly in H^1 .

The tensors $A_\varepsilon = (F_{\text{el},\varepsilon} - I)/\varepsilon$ and $\widehat{A}_\varepsilon = (\widehat{F}_{\text{el},\varepsilon} - I)/\varepsilon$ fulfill

$$A_\varepsilon = \frac{1}{\varepsilon}((I + \varepsilon \nabla u_\varepsilon)(I + \varepsilon z_\varepsilon)^{-1} - I), \quad \widehat{A}_\varepsilon = \frac{1}{\varepsilon}((I + \varepsilon \nabla \widehat{u}_\varepsilon)(I + \varepsilon \widehat{z}_\varepsilon)^{-1} - I)$$

and are hence both bounded in L^2 by (2.7).

Fix now δ and let $c_{\text{el}}(\delta)$ and $c_{\text{h}}(\delta)$ be given by conditions (2.1e) and (2.6d), respectively. For all $\varepsilon > 0$ we define the sets

$$U_\varepsilon^\delta := \left\{ x \in \Omega \mid |\varepsilon A_\varepsilon(x)| + |\varepsilon \widehat{A}_\varepsilon(x)| \leq c_{\text{el}}(\delta) \right\},$$

$$Z_\varepsilon^\delta := \left\{ x \in \Omega \mid |\varepsilon z_\varepsilon(x)| + |\varepsilon \widehat{z}_\varepsilon(x)| \leq c_{\text{h}}(\delta) \right\},$$

We refer to the latter as *good sets* as strains are there under control and we can replace the nonlinear densities W_{el} and W_{h} by their quadratic expansions via (2.1e) and (2.6d). In particular, on the good sets the quadratic character of the expansions will entail the control of the difference of the energy contributions by means of a suitable cancellation (*quadratic trick*). On the other hand, we term *bad sets* the corresponding complements $\Omega \setminus U_\varepsilon^\delta$ and $\Omega \setminus Z_\varepsilon^\delta$ where the quadratic expansions are a priori not available. Using some nontrivial cancellations, we will show that the difference of the energy contributions on the bad sets is infinitesimal. Note preliminarily that the integrands on the bad sets blow up while the bad sets have small measure. Indeed,

$$|\Omega \setminus U_\varepsilon^\delta| = \int_{\Omega \setminus U_\varepsilon^\delta} 1 \, dx \leq \frac{\varepsilon^2}{c_{\text{el}}^2(\delta)} \int_{\Omega} (|A_\varepsilon| + |\widehat{A}_\varepsilon|)^2 \, dx \leq \frac{c\varepsilon^2}{c_{\text{el}}^2(\delta)}, \quad (3.16)$$

$$|\Omega \setminus Z_\varepsilon^\delta| = \int_{\Omega \setminus Z_\varepsilon^\delta} 1 \, dx \leq \frac{\varepsilon^2}{c_{\text{h}}^2(\delta)} \int_{\Omega} (|z_\varepsilon| + |\widehat{z}_\varepsilon|)^2 \, dx \leq \frac{c\varepsilon^2}{c_{\text{h}}^2(\delta)}. \quad (3.17)$$

Step 2: Treatment of the dissipation term. As $\widehat{z}_\varepsilon = z_\varepsilon$ on $\Omega \setminus \Omega_\varepsilon$ one has that

$$\mathcal{D}_\varepsilon(z_\varepsilon, \widehat{z}_\varepsilon) = \frac{1}{\varepsilon} \int_{\Omega_\varepsilon} D(I, \exp(\varepsilon \tilde{z})) \, dx \leq \frac{1}{\varepsilon} \int_{\Omega} D(I, \exp(\varepsilon \tilde{z})) \, dx. \quad (3.18)$$

In the construction of the recovery sequence in the proof of Lemma 3.4 we have proved that

$$\limsup_{\varepsilon \rightarrow 0} \frac{1}{\varepsilon} D(I, \exp(\varepsilon \tilde{z})) \leq R(\tilde{z}). \quad (3.19)$$

Eventually, by taking the lim sup in relation (3.18) and using (3.19) we have proved that

$$\begin{aligned} \limsup_{\varepsilon \rightarrow 0} \mathcal{D}_\varepsilon(z_\varepsilon, \widehat{z}_\varepsilon) &= \limsup_{\varepsilon \rightarrow 0} \frac{1}{\varepsilon} \int_{\Omega} D(I, \exp(\varepsilon \tilde{z})) \, dx \\ &\leq \int_{\Omega} R(\tilde{z}) \, dx = \mathcal{D}_0(z_0, \widehat{z}_0). \end{aligned} \quad (3.20)$$

Step 3: Limsup for the differences of the elastic energy terms. Let us start by rewriting the tensors A_ε as

$$A_\varepsilon = \nabla u_\varepsilon - z_\varepsilon + w_\varepsilon - \varepsilon \nabla u_\varepsilon z_\varepsilon + \varepsilon \nabla u_\varepsilon w_\varepsilon$$

where w_ε is given by (3.6). On the other hand, as regards the tensors \widehat{A}_ε we have that

$$\begin{aligned}\widehat{A}_\varepsilon &= \frac{1}{\varepsilon}((I + \varepsilon \nabla \widehat{u}_\varepsilon)(I - \varepsilon z_\varepsilon + \varepsilon w_\varepsilon) \exp(-\varepsilon \tilde{z}) - I) \\ &= (\nabla \widehat{u}_\varepsilon - z_\varepsilon + w_\varepsilon - \varepsilon \nabla \widehat{u}_\varepsilon z_\varepsilon + \varepsilon \nabla \widehat{u}_\varepsilon w_\varepsilon) \exp(-\varepsilon \tilde{z}) \\ &\quad + \frac{1}{\varepsilon}(\exp(-\varepsilon \tilde{z}) - I) \quad \text{on } \Omega_\varepsilon \\ \widehat{A}_\varepsilon &= \frac{1}{\varepsilon}((I + \varepsilon \nabla \widehat{u}_\varepsilon)(I - \varepsilon z_\varepsilon + \varepsilon w_\varepsilon) - I) \\ &= \nabla \widehat{u}_\varepsilon - z_\varepsilon + w_\varepsilon - \varepsilon \nabla \widehat{u}_\varepsilon z_\varepsilon + \varepsilon \nabla \widehat{u}_\varepsilon w_\varepsilon \quad \text{on } \Omega \setminus \Omega_\varepsilon.\end{aligned}$$

Hence, one can compute that

$$\begin{aligned}\widehat{A}_\varepsilon - A_\varepsilon &= (\nabla \widehat{u}_\varepsilon - \nabla u_\varepsilon)(I - \varepsilon z_\varepsilon + \varepsilon w_\varepsilon) + \frac{1}{\varepsilon}(\exp(-\varepsilon \tilde{z}) - I) \\ &\quad + (\nabla \widehat{u}_\varepsilon - z_\varepsilon + w_\varepsilon - \varepsilon \nabla \widehat{u}_\varepsilon z_\varepsilon + \varepsilon \nabla \widehat{u}_\varepsilon w_\varepsilon)(\exp(-\varepsilon \tilde{z}) - I) \quad \text{on } \Omega_\varepsilon \\ \widehat{A}_\varepsilon - A_\varepsilon &= (\nabla \widehat{u}_\varepsilon - \nabla u_\varepsilon)(I - \varepsilon z_\varepsilon + \varepsilon w_\varepsilon) \quad \text{on } \Omega \setminus \Omega_\varepsilon.\end{aligned}$$

In particular, owing to convergence (3.15) and the L^∞ bounds for $\varepsilon z_\varepsilon$ and $\varepsilon w_\varepsilon$ (see the discussion after (3.6)) we have that $(\nabla \widehat{u}_\varepsilon - \nabla u_\varepsilon)(I - \varepsilon z_\varepsilon + \varepsilon w_\varepsilon)$ converges to $\nabla \tilde{u}$ strongly in L^2 . Thus, by recalling that $w_\varepsilon \rightarrow 0$ weakly in L^2 it is a standard matter to check that

$$\widehat{A}_\varepsilon + A_\varepsilon \rightarrow (\nabla \widehat{u}_0 - \widehat{z}_0) + (\nabla u_0 - z_0) \quad \text{weakly in } L^2(\Omega; \mathbb{R}^{d \times d}), \quad (3.21)$$

$$\widehat{A}_\varepsilon - A_\varepsilon \rightarrow \nabla \tilde{u} - \tilde{z} \quad \text{strongly in } L^2(\Omega; \mathbb{R}^{d \times d}). \quad (3.22)$$

On the good set U_ε^δ we will use the assumption (2.1e) in order to have that

$$\begin{aligned}W_{\text{el}}^\varepsilon(\widehat{A}_\varepsilon) - W_{\text{el}}^\varepsilon(A_\varepsilon) &\leq |\widehat{A}_\varepsilon|_{\mathbb{C}}^2 - |A_\varepsilon|_{\mathbb{C}}^2 + \delta(|\widehat{A}_\varepsilon|_{\mathbb{C}}^2 + |A_\varepsilon|_{\mathbb{C}}^2) \\ &= \frac{1}{2}(\widehat{A}_\varepsilon - A_\varepsilon) : \mathbb{C}(\widehat{A}_\varepsilon + A_\varepsilon) + \delta(|\widehat{A}_\varepsilon|_{\mathbb{C}}^2 + |A_\varepsilon|_{\mathbb{C}}^2).\end{aligned} \quad (3.23)$$

Let us now argue on the bad set $\Omega \setminus U_\varepsilon^\delta$ by defining

$$G_{1,\varepsilon} := (I + \varepsilon \nabla \widehat{u}_\varepsilon)(I + \varepsilon \nabla u_\varepsilon)^{-1}, \quad G_{2,\varepsilon} := (I + \varepsilon z_\varepsilon)(I + \varepsilon \widehat{z}_\varepsilon)^{-1}.$$

The energy bound (3.10), together with assumption (2.1a), implies that $I + \varepsilon \nabla u_\varepsilon$ is invertible almost everywhere. Note that $G_{1,\varepsilon}$ and $G_{2,\varepsilon}$ are chosen in such a way that $\widehat{F}_{\text{el},\varepsilon} = G_{1,\varepsilon} F_{\text{el},\varepsilon} G_{2,\varepsilon}$. We readily compute that

$$G_{1,\varepsilon} - I = \nabla \psi_\varepsilon(\varphi_\varepsilon) \nabla \varphi_\varepsilon (I + \varepsilon \nabla u_\varepsilon)^{-1} - I = \nabla \psi_\varepsilon(\varphi_\varepsilon) - I = \varepsilon \nabla \tilde{u}(\varphi_\varepsilon)$$

so that $\|G_{1,\varepsilon} - I\|_{L^\infty(\Omega \setminus U_\varepsilon^\delta; \mathbb{R}^{d \times d})} = \varepsilon \|\nabla \tilde{u}(\varphi_\varepsilon)\|_{L^\infty(\Omega \setminus U_\varepsilon^\delta; \mathbb{R}^{d \times d})} \leq c\varepsilon$. Moreover, one has that

$$G_{2,\varepsilon} = \begin{cases} \exp(-\varepsilon \tilde{z}) & \text{on } (\Omega \setminus U_\varepsilon^\delta) \cap \Omega_\varepsilon, \\ I & \text{on } \Omega \setminus (U_\varepsilon^\delta \cup \Omega_\varepsilon). \end{cases}$$

Hence, $\|G_{2,\varepsilon} - I\|_{L^\infty(\Omega \setminus U_\varepsilon^\delta; \mathbb{R}_{\text{dev}}^{d \times d})} \leq c\varepsilon$ as well. Next, estimate (4.1) and bound (3.10) allow us to control the elastic part of the energy on the bad set $\Omega \setminus U_\varepsilon^\delta$ (where ∇u_ε

and z_ε are not under control) by cancellation. For this we employ the multiplicative estimate (2.1d) provided in (4.1):

$$\begin{aligned}
 \int_{\Omega \setminus U_\varepsilon^\delta} (W_{\text{el}}^\varepsilon(\widehat{A}_\varepsilon) - W_{\text{el}}^\varepsilon(A_\varepsilon)) \, dx &= \frac{1}{\varepsilon^2} \int_{\Omega \setminus U_\varepsilon^\delta} (W_{\text{el}}(\widehat{F}_{\text{el},\varepsilon}) - W_{\text{el}}(F_{\text{el},\varepsilon})) \, dx \\
 &= \frac{1}{\varepsilon^2} \int_{\Omega \setminus U_\varepsilon^\delta} (W_{\text{el}}(G_{1,\varepsilon} F_{\text{el},\varepsilon} G_{2,\varepsilon}) - W_{\text{el}}(F_{\text{el},\varepsilon})) \, dx \\
 &\stackrel{(4.1)}{\leq} \frac{c_7}{\varepsilon^2} \int_{\Omega \setminus U_\varepsilon^\delta} (W_{\text{el}}(F_{\text{el},\varepsilon}) + c_8)(|G_{1,\varepsilon} - I| + |G_{2,\varepsilon} - I|) \, dx \\
 &\leq c_7 \left(\frac{1}{\varepsilon^2} \int_{\Omega} W_{\text{el}}(F_{\text{el},\varepsilon}) \, dx + \frac{c_8}{\varepsilon^2} |\Omega \setminus U_\varepsilon^\delta| \right) (\|G_{1,\varepsilon} - I\|_{L^\infty} + \|G_{2,\varepsilon} - I\|_{L^\infty}) \\
 &\stackrel{(3.10) \& (3.16)}{\leq} c \left(1 + \frac{1}{c_{\text{el}}^2(\delta)} \right) \varepsilon.
 \end{aligned} \tag{3.24}$$

Thus, we have controlled the difference of the energy contributions in the bad set $\Omega \setminus U_\varepsilon^\delta$ where the gradients are big.

Finally, by using convergences (3.21)-(3.22), equation (3.23) on the good set U_ε^δ , relation (3.24) on the bad set $\Omega \setminus U_\varepsilon^\delta$, and the L^2 boundedness of \widehat{A}_ε and A_ε , we conclude that

$$\begin{aligned}
 &\limsup_{\varepsilon \rightarrow 0} \left(\int_{\Omega} W_{\text{el}}^\varepsilon(\widehat{A}_\varepsilon) \, dx - \int_{\Omega} W_{\text{el}}^\varepsilon(A_\varepsilon) \, dx \right) \\
 &\stackrel{(3.23)}{\leq} \limsup_{\varepsilon \rightarrow 0} \left(\frac{1}{2} \int_{U_\varepsilon^\delta} (\widehat{A}_\varepsilon - A_\varepsilon) : \mathbb{C}(\widehat{A}_\varepsilon + A_\varepsilon) \, dx + c\delta \right. \\
 &\quad \left. + \int_{\Omega \setminus U_\varepsilon^\delta} (W_{\text{el}}^\varepsilon(\widehat{A}_\varepsilon) - W_{\text{el}}^\varepsilon(A_\varepsilon)) \, dx \right) \\
 &\stackrel{(3.24)}{\leq} \limsup_{\varepsilon \rightarrow 0} \left(\frac{1}{2} \int_{U_\varepsilon^\delta} (\widehat{A}_\varepsilon - A_\varepsilon) : \mathbb{C}(\widehat{A}_\varepsilon + A_\varepsilon) \, dx + c\delta + c \left(1 + \frac{1}{c_{\text{el}}^2(\delta)} \right) \varepsilon \right) \\
 &\leq \frac{1}{2} \int_{\Omega} (\nabla \tilde{u} - \tilde{z}) : \mathbb{C}(\nabla(\widehat{u}_0 + u_0) - (\widehat{z}_0 + z_0)) \, dx + c\delta \\
 &= \int_{\Omega} |\nabla \widehat{u}_0^{\text{sym}} - \widehat{z}_0^{\text{sym}}|_{\mathbb{C}}^2 \, dx - \int_{\Omega} |\nabla u_0^{\text{sym}} - z_0^{\text{sym}}|_{\mathbb{C}}^2 \, dx + c\delta
 \end{aligned} \tag{3.25}$$

where we have made use of relation (2.3).

Step 4: Upper bound on the hardening energy term. Let us now turn our attention to the hardening part of the energy. On the good set Z_ε^δ we have that

$$\begin{aligned}
 W_{\text{h}}^\varepsilon(\widehat{z}_\varepsilon) - W_{\text{h}}^\varepsilon(z_\varepsilon) &\leq |\widehat{z}_\varepsilon|_{\mathbb{H}}^2 - |z_\varepsilon|_{\mathbb{H}}^2 + \delta(|\widehat{z}_\varepsilon|_{\mathbb{H}}^2 + |z_\varepsilon|_{\mathbb{H}}^2) \\
 &= \frac{1}{2}(\widehat{z}_\varepsilon - z_\varepsilon) : \mathbb{H}(\widehat{z}_\varepsilon + z_\varepsilon) + \delta(|\widehat{z}_\varepsilon|_{\mathbb{H}}^2 + |z_\varepsilon|_{\mathbb{H}}^2).
 \end{aligned} \tag{3.26}$$

As regards the bad set $\Omega \setminus Z_\varepsilon^\delta$ one has that

$$W_{\text{h}}^\varepsilon(\widehat{z}_\varepsilon) - W_{\text{h}}^\varepsilon(z_\varepsilon) = \begin{cases} \frac{1}{\varepsilon^2} \widetilde{W}_{\text{h}}(\exp(\varepsilon \tilde{z})(I + \varepsilon z_\varepsilon)) - \frac{1}{\varepsilon^2} \widetilde{W}_{\text{h}}(I + \varepsilon z_\varepsilon) & \text{on } (\Omega \setminus Z_\varepsilon^\delta) \cap \Omega_\varepsilon \\ 0 & \text{on } \Omega \setminus (Z_\varepsilon^\delta \cup \Omega_\varepsilon). \end{cases}$$

Hence, by exploiting the local Lipschitz continuity of \widetilde{W}_h we have that

$$\begin{aligned} \int_{\Omega \setminus Z_\varepsilon^\delta} (W_h^\varepsilon(\widehat{z}_\varepsilon) - W_h^\varepsilon(z_\varepsilon)) \, dx &\leq \frac{c}{\varepsilon^2} \int_{\Omega \setminus Z_\varepsilon^\delta} |\exp(\varepsilon \widehat{z}) - I| |I + \varepsilon z_\varepsilon| \, dx \\ &\leq \frac{c}{\varepsilon^2} |\Omega \setminus Z_\varepsilon^\delta| \frac{c\varepsilon}{c_h^2(\delta)} \stackrel{(3.17)}{\leq} \frac{c\varepsilon}{c_h^2(\delta)}. \end{aligned} \quad (3.27)$$

Eventually, owing to convergences (3.12)-(3.13) we compute that

$$\begin{aligned} &\limsup_{\varepsilon \rightarrow 0} \left(\int_{\Omega} W_h^\varepsilon(\widehat{z}_\varepsilon) \, dx - \int_{\Omega} W_h^\varepsilon(z_\varepsilon) \, dx \right) \\ &\stackrel{(3.26)}{\leq} \limsup_{\varepsilon \rightarrow 0} \left(\int_{Z_\varepsilon^\delta} \frac{1}{2} (\widehat{z}_\varepsilon - z_\varepsilon) : \mathbb{H}(\widehat{z}_\varepsilon + z_\varepsilon) \, dx + c\delta \right. \\ &\quad \left. + \int_{\Omega \setminus Z_\varepsilon^\delta} (W_h^\varepsilon(\widehat{z}_\varepsilon) - W_h^\varepsilon(z_\varepsilon)) \, dx \right) \\ &\stackrel{(3.27)}{\leq} \limsup_{\varepsilon \rightarrow 0} \left(\int_{Z_\varepsilon^\delta} \frac{1}{2} (\widehat{z}_\varepsilon - z_\varepsilon) : \mathbb{H}(\widehat{z}_\varepsilon + z_\varepsilon) \, dx + c\delta + \frac{c\varepsilon}{c_{\text{el}}^2(\delta)} \right) \\ &= \int_{\Omega} \frac{1}{2} \widehat{z} : \mathbb{H}(\widehat{z}_0 + z_0) \, dx + c\delta = \int_{\Omega} |\widehat{z}_0|_{\mathbb{H}}^2 \, dx - \int_{\Omega} |z_0|_{\mathbb{H}}^2 \, dx + c\delta. \end{aligned} \quad (3.28)$$

Step 5: Conclusion of the proof. By collecting relations (3.25) and (3.28), and recalling that $\langle \ell(t), u_\varepsilon - \widehat{u}_\varepsilon \rangle \rightarrow \langle \ell(t), u_0 - \widehat{u}_0 \rangle$ we have proved that

$$\limsup_{\varepsilon \rightarrow 0} \left(\mathcal{E}_\varepsilon(t, \widehat{u}_\varepsilon, \widehat{z}_\varepsilon) - \mathcal{E}_\varepsilon(t, u_\varepsilon, z_\varepsilon) \right) \leq \left(\mathcal{E}_0(t, \widehat{u}_0, \widehat{z}_0) - \mathcal{E}_0(t, u_0, z_0) \right) + c\delta.$$

Finally, the assertion (3.11) follows by taking $\delta \rightarrow 0$ and employing (3.20). \square

3.4. Proof of Theorem 2.2. Owing to the the above-obtained Γ -liminf and mutual-recovery-sequence results, the proof of Theorem 2.2 now follows along the lines of the general theory of [MRS08]. We limit ourselves to sketch the main points of the argument and refer the reader to [MRS08] for the details.

Let $(u_\varepsilon, z_\varepsilon)$ be a sequence of finite-plasticity solutions. The coercivity of the energy (3.1) entails an a priori bound on $(u_\varepsilon, z_\varepsilon)$. In particular, we have the following.

Corollary 3.7 (A priori bound). *There exists $c > 0$ such that all finite-plasticity solutions $(u_\varepsilon, z_\varepsilon)$ fulfill*

$$\forall t \in [0, T] : \quad \|u_\varepsilon(t)\|_{H^1} + \|z_\varepsilon(t)\|_{L^2} + \|\varepsilon z_\varepsilon(t)\|_{L^\infty} + \text{Diss}_{\mathcal{D}_\varepsilon}(z_\varepsilon; [0, t]) \leq c. \quad (3.29)$$

Proof. We exploit the energy balance (2.16) and the bound (3.1) in order to get that, for all $t \in [0, T]$,

$$\begin{aligned}
 & \|\nabla u_\varepsilon(t)\|_{L^2}^2 + \|z_\varepsilon(t)\|_{L^2}^2 + \|\varepsilon z_\varepsilon(t)\|_{L^\infty}^2 + \text{Diss}_{\mathcal{D}_\varepsilon}(z_\varepsilon; [0, t]) \\
 & \stackrel{(3.1)}{\leq} c(1 + \mathcal{W}_\varepsilon(u_\varepsilon(t), z_\varepsilon(t))) + \text{Diss}_{\mathcal{D}_\varepsilon}(z_\varepsilon; [0, t]) \\
 & \leq c(1 + \mathcal{E}_\varepsilon(t, u_\varepsilon(t), z_\varepsilon(t)) + \langle \ell(t), u_\varepsilon(t) \rangle + \text{Diss}_{\mathcal{D}_\varepsilon}(z_\varepsilon; [0, t])) \\
 & \stackrel{(2.16)}{=} c \left(1 + \mathcal{E}_\varepsilon(0, u_\varepsilon^0, z_\varepsilon^0) + \langle \ell(t), u_\varepsilon(t) \rangle - \int_0^t \langle \dot{\ell}, u_\varepsilon \rangle ds \right) \\
 & \leq c \left(1 + \mathcal{E}_\varepsilon(0, u_\varepsilon^0, z_\varepsilon^0) + \|\ell(t)\|_{H^{-1}} \|u_\varepsilon(t)\|_{H^1} + \int_0^t \|\dot{\ell}\|_{H^{-1}} \|u_\varepsilon\|_{H^1} ds \right)
 \end{aligned}$$

so that the assertion follows by Gronwall Lemma. \square

Owing to the a priori bound (3.29), we may now exploit the generalized version of Helly's Selection Principle in [MRS08, Thm. A.1] (consider also the comments thereafter) and deduce that, at least for some nonrelabeled subsequence, and all $s, t \in [0, T]$ with $s < t$,

$$\begin{aligned}
 \delta_0(t) &:= \lim_{\varepsilon \rightarrow 0} \text{Diss}_{\mathcal{D}_\varepsilon}(z_\varepsilon; [0, t]), \\
 z_\varepsilon(t) &\rightarrow z_0(t) \quad \text{weakly in } \mathcal{Z}, \\
 \text{Diss}_{\mathcal{D}_0}(z_0; [s, t]) &\leq \delta_0(t) - \delta_0(s),
 \end{aligned}$$

Moreover, by letting $t \in [0, T]$ be fixed we may extract a further subsequence (still not relabeled, possibly depending on t) such that $u_\varepsilon(t) \rightarrow u_*$ weakly in \mathcal{U} . We now check that indeed $(u_*, z_0(t)) \in \mathcal{S}_0(t)$. To this aim, by density it suffices to consider competitors $(\widehat{u}_0, \widehat{z}_0) = (u_*, z_0(t)) + (\tilde{u}, \tilde{z})$ with (\tilde{u}, \tilde{z}) smooth and compactly supported. By applying Lemma 3.6 we find a mutual recovery sequence $(\widehat{u}_\varepsilon, \widehat{z}_\varepsilon)$ such that

$$\begin{aligned}
 & \mathcal{E}_0(t, \widehat{u}_0, \widehat{z}_0) - \mathcal{E}_0(t, u_*, z_0(t)) + \mathcal{D}_0(z_0(t), \widehat{z}_0) \\
 & \geq \limsup_{\varepsilon \rightarrow 0} (\mathcal{E}_\varepsilon(t, \widehat{u}_\varepsilon, \widehat{z}_\varepsilon) - \mathcal{E}_\varepsilon(t, u_\varepsilon(t), z_\varepsilon(t)) + \mathcal{D}_\varepsilon(z_\varepsilon(t), \widehat{z}_\varepsilon)) \geq 0
 \end{aligned} \tag{3.30}$$

where the last inequality follows from the stability (2.15) of $(u_\varepsilon(t), z_\varepsilon(t))$. Hence, we have proved that $(u_*, z_0(t)) \in \mathcal{S}_0(t)$. Note that, given $z_0(t) \in \mathcal{Z}$, as the functional $u \in \mathcal{U} \mapsto \mathcal{E}_0(t, u, z_0(t))$ is uniformly convex there exists a unique $u_0(t) \in \mathcal{U}$ such that $(u_0(t), z_0(t)) \in \mathcal{S}_0(t)$. From the fact that $(u_*, z_0(t)) \in \mathcal{S}_0(t)$ we conclude that $u_* \equiv u_0(t)$. In particular $u_\varepsilon(t) \rightarrow u_0(t)$ weakly in \mathcal{U} for all $t \in [0, T]$ and the whole sequence converges.

Let now be given a partition $\{0 = t_0 < t_1 < \dots < t_N = t\}$. By passing to the \liminf in the energy balance (2.16) and using Lemmas 3.3 and 3.5 we get that

$$\begin{aligned} & \mathcal{E}_0(t, u_0(t), z_0(t)) + \sum_{i=1}^N \mathcal{D}_0(z_0(t_i), z_0(t_{i-1})) \\ & \leq \liminf_{\varepsilon \rightarrow 0} \left(\mathcal{E}_\varepsilon(t, u_\varepsilon(t), z_\varepsilon(t)) + \sum_{i=1}^N \mathcal{D}_\varepsilon(z_\varepsilon(t_i), z_\varepsilon(t_{i-1})) \right) \\ & \leq \liminf_{\varepsilon \rightarrow 0} \left(\mathcal{E}_\varepsilon(0, u_\varepsilon^0, z_\varepsilon^0) - \int_0^t \langle \dot{\ell}, u_\varepsilon \rangle ds \right) = \mathcal{E}_0(0, u_0^0, z_0^0) - \int_0^t \langle \dot{\ell}, u_0 \rangle ds \end{aligned}$$

where for the last equality we have used (2.14) and the convergence of u_ε . Hence, the upper energy estimate follows by taking the sup among all partitions of the interval $[0, t]$. The lower energy estimate can classically recovered from stability as in [Mie05, Prop. 2.7]. This proves that (u_0, z_0) is a linearized-plasticity solution. In particular, as linearized-plasticity solutions are unique, the whole sequence $(u_\varepsilon, z_\varepsilon)$ converges and no extraction of subsequences is actually needed.

Along the lines of the proof of Theorem 2.2 (see also [MRS08, Thm. 3.1]) we also obtain the following convergences.

Corollary 3.8 (Improved convergences). *Under the assumptions of Theorem 2.2 we have that, for all $t \in [0, T]$,*

$$\int_{\Omega} (W_{\text{el}}^\varepsilon(A_\varepsilon) + W_{\text{h}}^\varepsilon(z_\varepsilon)) dx \rightarrow \int_{\Omega} (|\nabla u_0 - z_0|_{\mathbb{C}}^2 + |z_0|_{\mathbb{H}}^2) dx, \quad (3.31)$$

$$\text{Diss}_{\mathcal{D}_\varepsilon}(z_\varepsilon; [0, t]) \rightarrow \int_0^t R(\dot{z}) ds. \quad (3.32)$$

In particular, owing to the energy convergence (3.31) we are in the position of deducing some strong convergence of finite-plasticity solutions to linearized-plasticity solutions.

Corollary 3.9 (Strong convergence). *Under the assumptions of Theorem 2.2 for all $t \in [0, T]$ we have that $(u_\varepsilon(t), z_\varepsilon(t)) \rightarrow (u_0(t), z_0(t))$ strongly in $W^{1,p}(\Omega; \mathbb{R}^d) \times L^p(\Omega; \mathbb{R}^{d \times d})$ for all $p \in [1, 2)$.*

Proof. Let ν denote the Young measure generated by the sequence $(A_\varepsilon, z_\varepsilon)$ and define the measure $\nu^{\text{sym}}(A^s, Z) := \nu(A^s \oplus \mathbb{R}_{\text{anti}}^{d \times d}, Z)$ for all Borel sets $(A^s, Z) \subset \mathbb{R}_{\text{sym}}^{d \times d} \times \mathbb{R}^{d \times d}$. Note that ν^{sym} is indeed the Young measure generated by $(A_\varepsilon^{\text{sym}}, z_\varepsilon)$. By using the lower semicontinuity Lemma 4.2 and the energy convergence (3.31) we deduce that

$$\begin{aligned} & \int_{\Omega} \left(\int_{\mathbb{R}_{\text{sym}}^{d \times d} \times \mathbb{R}^{d \times d}} (|A^{\text{sym}}|_{\mathbb{C}}^2 + |z|_{\mathbb{H}}^2) d\nu_x^{\text{sym}}(A^{\text{sym}}, z) \right) dx \\ & = \int_{\Omega} \left(\int_{\mathbb{R}^{d \times d} \times \mathbb{R}^{d \times d}} (|A|_{\mathbb{C}}^2 + |z|_{\mathbb{H}}^2) d\nu_x(A, z) \right) dx \\ & \leq \liminf_{\varepsilon \rightarrow 0} \int_{\Omega} (W_{\text{el}}^\varepsilon(A_\varepsilon) + W_{\text{h}}^\varepsilon(z_\varepsilon)) dx \stackrel{(3.31)}{=} \int_{\Omega} (|\nabla u_0 - z_0|_{\mathbb{C}}^2 + |z_0|_{\mathbb{H}}^2) dx. \end{aligned} \quad (3.33)$$

Recall from (3.7) that

$$A_\varepsilon^{\text{sym}} = \nabla u_\varepsilon^{\text{sym}} - z_\varepsilon^{\text{sym}} - \varepsilon(\nabla u_\varepsilon z_\varepsilon - \nabla u_\varepsilon w_\varepsilon)^{\text{sym}}$$

where the remainder term $\varepsilon(\nabla u_\varepsilon z_\varepsilon - \nabla u_\varepsilon w_\varepsilon)^{\text{sym}}$ converges strongly to 0 in L^p for all $p \in [1, 2)$. Hence, the barycenter of ν^{sym} is clearly $(\nabla u_0^{\text{sym}} - z_0^{\text{sym}}, z_0)$.

We readily check that the measure ν^{sym} is concentrated in its barycenter. Indeed, if this was not the case, by uniform convexity we would have that

$$\begin{aligned} & \int_{\Omega} (|\nabla u_0^{\text{sym}} - z_0^{\text{sym}}|_{\mathbb{C}}^2 + |z_0|_{\mathbb{H}}^2) \, dx \\ & < \int_{\Omega} \left(\int_{\mathbb{R}_{\text{sym}}^{d \times d} \times \mathbb{R}^{d \times d}} (|A^{\text{sym}}|_{\mathbb{C}}^2 + |z|_{\mathbb{H}}^2) \, d\nu_x^{\text{sym}}(A^{\text{sym}}, z) \right) \, dx \end{aligned}$$

contradicting relation (3.33). Here we have used positive definiteness from (2.5) and (2.9). As ν^{sym} is concentrated, we exploit [AGS08, Thm. 5.4.4.iii, p. 127] and deduce that

$$\int_{\Omega} f(x, A_\varepsilon^{\text{sym}}(x), z_\varepsilon(x)) \, dx \rightarrow \int_{\Omega} \left(\int_{\mathbb{R}_{\text{sym}}^{d \times d} \times \mathbb{R}^{d \times d}} f(x, A^{\text{sym}}, z) \, d\nu_x^{\text{sym}}(A^{\text{sym}}, z) \right) \, dx$$

along with the choice

$$f(x, A^{\text{sym}}, z) := |(\nabla u_0^{\text{sym}}(x) - z_0^{\text{sym}}(x), z_0^{\text{sym}}(x)) - (A^{\text{sym}} - z^{\text{sym}}, z)|^p.$$

Hence, we have that $(A_\varepsilon^{\text{sym}}, z_\varepsilon) \rightarrow (\nabla u_0^{\text{sym}} - z_0^{\text{sym}}, z_0)$ strongly in $L^p(\Omega; \mathbb{R}_{\text{sym}}^{d \times d}) \times L^p(\Omega; \mathbb{R}^{d \times d})$ for all $p \in [1, 2)$. In particular,

$$\nabla u_\varepsilon^{\text{sym}} = A_\varepsilon^{\text{sym}} + z_\varepsilon^{\text{sym}} + \varepsilon(\nabla u_\varepsilon z_\varepsilon - \nabla u_\varepsilon w_\varepsilon)^{\text{sym}} \rightarrow \nabla u_0^{\text{sym}} \text{ strongly in } L^p$$

for all $p \in [1, 2)$ and the assertion follows by Korn's inequality. \square

3.5. Sketch of the proof of Theorem 2.3. The argument for Theorem 2.2 can be adapted to prove Theorem 2.3 as well. The only notable difference is that one has to cope with the fact that the piecewise constant interpolants $(\bar{u}_\varepsilon, \bar{z}_\varepsilon)$ of the approximate incremental minimizers need not be stable but rather just *approximately stable*. More precisely, from (2.17) and the triangle inequality we have that

$$\forall (\hat{u}, \hat{z}) \in \mathcal{Q} : \mathcal{E}_\varepsilon(t, \hat{u}, \hat{z}) - \mathcal{E}_\varepsilon(t, \bar{u}_\varepsilon(t), \bar{z}_\varepsilon(t)) + \mathcal{D}_\varepsilon(\bar{z}_\varepsilon(t), \hat{z}) \geq -\tau_\varepsilon \alpha_\varepsilon.$$

By coordinating to the sequence $(\bar{u}_\varepsilon(t), \bar{z}_\varepsilon(t))$ a mutual recovery sequence $(\hat{u}_\varepsilon, \hat{z}_\varepsilon)$ via Lemma 3.6 (with $(\bar{u}_\varepsilon(t), \bar{z}_\varepsilon(t))$ instead of $(u_\varepsilon(t), z_\varepsilon(t))$) the lower bound (3.30) still follows as $\tau_\varepsilon \alpha_\varepsilon \rightarrow 0$. Hence, the stability of the limit can be recovered. Finally, improved and strong convergences in the spirit of Corollaries 3.8-3.9 can be established as well.

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4. APPENDIX

4.1. Estimate on left and right multiplication. In the proof of Theorems 2.2-2.3 we have made use of the following estimate combining left and right multiplication.

Lemma 4.1. *Assume (2.1a) and (2.1d). Then,*

$$\begin{aligned} & \exists c_7, c_8, \gamma > 0 \quad \forall G_1, G_2 \in B_\gamma(I) \quad \forall F \in \text{GL}_+(d) : \\ & |W_{\text{el}}(G_1 F G_2) - W_{\text{el}}(F)| \leq c_7(W(F) + c_8)(|G_1 - I| + |G_2 - I|). \end{aligned} \quad (4.1)$$

Proof. Following [Bal02, Lemma 2.5], we find positive constants $c_0, \widehat{c}_0, \gamma$ such that, for all $G \in B_\gamma(I)$ and all $F \in \text{GL}_+(d)$, one has that

$$W_{\text{el}}(GF) \leq \widehat{c}_0 W_{\text{el}}(F) + c_0, \quad W_{\text{el}}(FG) \leq \widehat{c}_0 W_{\text{el}}(F) + c_0, \quad (4.2)$$

$$|\partial_F W(GF) F^\top| \leq \widehat{c}_0 W_{\text{el}}(F) + c_0, \quad (4.3)$$

$$|F^\top \partial_F W(FG)| \leq \widehat{c}_0 W_{\text{el}}(F) + c_0. \quad (4.4)$$

For $s \in [0, 1]$, let now $H_j(s) := (1-s)I + sG_j$ for $j = 1, 2$, and note that $H_j \in B_\gamma(I)$. As the derivative $H'_j = G_j - I$ is constant we can compute that

$$\begin{aligned} W_{\text{el}}(G_1 F G_2) - W_{\text{el}}(F) &= \int_0^1 \frac{d}{ds} W_{\text{el}}(H_1(s) F H_2(s)) ds \\ &= \int_0^1 \partial_F W_{\text{el}}(H_1 F H_2) : (H'_1 F H_2 + H_1 F H'_2) ds \\ &= \int_0^1 \partial_F W_{\text{el}}(H_1 F H_2) (F H_2)^\top ds : H'_1 + \int_0^1 (H_1 F)^\top \partial_F W_{\text{el}}(H_1 F H_2) ds : H'_2. \end{aligned}$$

We control the above right-hand side as

$$\begin{aligned} \left| \int_0^1 \partial_F W_{\text{el}}(H_1 F H_2) (F H_2)^\top ds : H'_1 \right| &\stackrel{(4.3)}{\leq} \left(\int_0^1 (\widehat{c}_0 W_{\text{el}}(F H_2) + c_0) ds \right) |G_1 - I| \\ &\stackrel{(4.2)}{\leq} (\widehat{c}_0^2 W_{\text{el}}(F) + c_0 \widehat{c}_0 + c_0) |G_1 - I|, \\ \left| \int_0^1 (H_1 F)^\top \partial_F W_{\text{el}}(H_1 F H_2) ds : H'_2 \right| &\stackrel{(4.4)}{\leq} \left(\int_0^1 (\widehat{c}_0 W_{\text{el}}(H_1 F) + c_0) ds \right) |G_2 - I| \\ &\stackrel{(4.2)}{\leq} (\widehat{c}_0^2 W_{\text{el}}(F) + c_0 \widehat{c}_0 + c_0) |G_2 - I|, \end{aligned}$$

whence the assertion follows. \square

4.2. Lower semicontinuity tool. In Section 3 the following lower-semicontinuity lemma is used.

Lemma 4.2 (Lower-semicontinuity). *Let $f_0, f_\varepsilon : \mathbb{R}^n \rightarrow [0, \infty]$ be lower semicontinuous,*

$$\forall v_0 \in \mathbb{R}^n : \quad f_0(v_0) \leq \inf_{\varepsilon \rightarrow 0} \left\{ \liminf_{\varepsilon \rightarrow 0} f_\varepsilon(v_\varepsilon) \mid v_\varepsilon \rightarrow v_0 \right\},$$

and $w_\varepsilon \rightarrow w_0$ weakly in $L^1(\Omega; \mathbb{R}^n)$. Denoting by ν the Young measure generated by w_ε we have that

$$\int_\Omega \left(\int_{\mathbb{R}^n} f_0(w) d\nu_x(w) \right) dx \leq \liminf_{\varepsilon \rightarrow 0} \int_\Omega f_\varepsilon(w_\varepsilon) dx.$$

In particular, if f_0 is convex we have

$$\int_{\Omega} f_0(w_0) \, dx \leq \liminf_{\varepsilon \rightarrow 0} \int_{\Omega} f_{\varepsilon}(w_{\varepsilon}) \, dx.$$

This lemma is in the same spirit of the results by BALDER [Bal84a, Thm. 1] and IOFFE [Iof77] and can be proved via augmenting the variables by including the parameter ε . The reader is referred to [Ste08, Thm 4.3, Cor. 4.4] or [MRS09, Lemma 3.1] for a proof in the case $d = 1$. In case of local uniform convergence, a proof can be found in [Li96].

REFERENCES

- [ADD11] V. Agostiniani, G. Dal Maso, and A. DeSimone. Linear elasticity obtained from finite elasticity by Γ -convergence under weak coerciveness conditions. Preprint, 2011.
- [AD11] V. Agostiniani and A. DeSimone. Gamma-convergence of energies for nematic elastomers in the small strain limit. *Contin. Mech. Thermodyn.*, 2011. to appear.
- [AGS08] L. Ambrosio, N. Gigli, and G. Savaré. *Gradient flows in metric spaces and in the space of probability measures*. Lectures in Mathematics ETH Zürich. Birkhäuser Verlag, Basel, 2008. Second edition.
- [Bal84a] E. J. Balder. A general approach to lower semicontinuity and lower closure in optimal control theory. *SIAM J. Control Optim.*, 22(4):570–598, 1984.
- [Bal84b] J. M. Ball. Minimizers and the Euler-Lagrange equations. In *Trends and applications of pure mathematics to mechanics (Palaiseau, 1983)*, volume 195 of *Lecture Notes in Phys.*, pages 1–4. Springer, Berlin, 1984.
- [Bal02] J. M. Ball. Some open problems in elasticity. In P. Newton et al., editor, *Geometry, mechanics, and dynamics. Volume in honor of the 60th birthday of J. E. Marsden*, pages 3–59. Springer, New York, NY, 2002.
- [BRM09] G. Bouchitté, T. Roubíček, and A. Mielke. A complete-damage model problem at small strains. *Z. Angew. Math. Phys.*, 60(2):205–236, 2009.
- [BSV07] A. Braides, M. Solci, and E. Vitali. A derivation of linear elastic energies from pair-interaction atomistic systems. *Netw. Heterog. Media*, 2(3):551–567, 2007.
- [CHM02] C. Carstensen, K. Hackl, and A. Mielke. Non-convex potentials and microstructures in finite-strain plasticity. *R. Soc. Lond. Proc. ser. A Math. Phys. Eng. Sci.*, 458(2018):299–317, 2002.
- [DNP02] G. Dal Maso, M. Negri, and D. Percivale. Linearized elasticity as Γ -limit of finite elasticity. *Set-Valued Anal.*, 10(2-3):165–183, 2002.
- [FJM02] G. Friesecke, R. D. James, and S. Müller. A theorem on geometric rigidity and the derivation of nonlinear plate theory from three-dimensional elasticity. *Comm. Pure Appl. Math.*, 55(11):1461–1506, 2002.
- [FM06] G. Francfort and A. Mielke. Existence results for a class of rate-independent material models with nonconvex elastic energies. *J. Reine Angew. Math.*, 595:55–91, 2006.
- [FPZ10] L. Freddi, R. Paroni, and C. Zanini. Dimension reduction of a crack evolution problem in a linearly elastic plate. *Asymptot. Anal.*, 70(1-2):101–123, 2010.
- [GN10] A. Gloria and S. Neukamm. Commutability of homogenization and linearization at identity in finite elasticity and applications. *Preprint MPI Leipzig*, 73, 2010.
- [GP06a] A. Giacomini and M. Ponsiglione. Discontinuous finite elements approximation of quasistatic crack growth in nonlinear elasticity. *Math. Models Methods Appl. Sci.*, 16:7–118, 2006.
- [GP06b] A. Giacomini and M. Ponsiglione. A Γ -convergence approach to stability of unilateral minimality properties in fracture mechanics and applications. *Arch. Ration. Mech. Anal.*, 180:399–447, 2006.
- [Hil50] R. Hill. *The mathematical theory of plasticity*. Clarendon Press, Oxford, 1950.
- [HR99] W. Han and B.D. Reddy. *Plasticity, Mathematical theory and numerical analysis*. Springer-Verlag, New York, 1999.
- [Iof77] A. D. Ioffe. On lower semicontinuity of integral functionals. I. *SIAM J. Control Optimization*, 15(4):521–538, 1977.

- [Joh76] C. Johnson. Existence theorems for plasticity problems. *J. Math. Pures Appl.*, 55:431–444, 1976.
- [KMR05] M. Kružík, A. Mielke, and T. Roubíček. Modelling of microstructure and its evolution in shape-memory-alloy single-crystals, in particular in CuAlNi. *Meccanica*, 40(4-6):389–418, 2005.
- [Lee69] E. Lee. Elastic-plastic deformation at finite strains. *J. Appl. Mech.*, 36:1–6, 1969.
- [Li96] Z. Li. A theorem on lower semicontinuity of integral functionals. *Proc. Roy. Soc. Edinburgh Sect. A*, 126(2):363–374, 1996.
- [LM11] M. Liero and A. Mielke. An evolutionary elastoplastic plate model derived via gamma convergence. *Math. Models Meth. Appl. Sci.*, 2011. to appear.
- [Lub90] J. Lubliner. *Plasticity theory*. Macmillan Publishing Company, New York, 1990.
- [Mar75] J. B. Martins. *Plasticity. Fundamentals and general results*. MIT Press, Cambridge, 1975.
- [Mie03] A. Mielke. Energetic formulation of multiplicative elasto-plasticity using dissipation distances. *Contin. Mech. Thermodyn.*, 15(4):351–382, 2003.
- [Mie04] A. Mielke. Existence of minimizers in incremental elasto-plasticity with finite strains. *SIAM J. Math. Anal.*, 36(2):384–404 (electronic), 2004.
- [Mie05] A. Mielke. Evolution of rate-independent systems. In C. Dafermos and E. Feireisl, editors, *Handbook of Differential Equations, evolutionary equations*, volume 2, pages 461–559. Elsevier, 2005.
- [MM06] A. Mielke and S. Müller. Lower semicontinuity and existence of minimizers in incremental finite-strain elastoplasticity. *ZAMM Z. Angew. Math. Mech.*, 86(3):233–250, 2006.
- [MM09] A. Mainik and A. Mielke. Global existence for rate-independent gradient plasticity at finite strain. *J. Nonlinear Sci.*, 19(3):221–248, 2009.
- [MN11] S. Müller and S. Neukamm. On the commutability of homogenization and linearization in finite elasticity. *arXiv:1011.3783*, 2011.
- [MR09] A. Mielke and T. Roubíček. Numerical approaches to rate-independent processes and applications in inelasticity. *M2NA Math. Model. Numer. Anal.*, 43(3):399–428, 2009.
- [MRS08] A. Mielke, T. Roubíček, and U. Stefanelli. Γ -limits and relaxations for rate-independent evolutionary problems. *Calc. Var. Partial Differential Equations*, 31(3):387–416, 2008.
- [MRS09] A. Mielke, R. Rossi, and G. Savaré. Modeling solutions with jumps for rate-independent systems on metric spaces. *Discrete Contin. Dyn. Syst. Ser. A*, 25(2):585–615, 2009.
- [MT04] A. Mielke and F. Theil. On rate-independent hysteresis models. *NoDEA, Nonlinear Diff. Equations Applications*, 11:151–189, 2004.
- [MT05] A. Mielke and A. M. Timofte. An energetic material model for time-dependent ferroelectric behavior: existence and uniqueness. *Math. Models Appl. Sci.*, 29:1393–1410, 2005.
- [Neu10] S. Neukamm. *Homogenization, linearization and dimensional reduction in elasticity with variational methods*. PhD thesis, Technische Universität München, 2010.
- [PT09] R. Paroni and G. Tomassetti. A variational justification of linear elasticity with residual stress. *J. Elast.*, 97:189–206, 2009.
- [PT11] R. Paroni and G. Tomassetti. From non-linear elasticity to linear elasticity with initial stress via Γ -convergence. *Continuum Mech. Thermodyn.*, in press, 2011.
- [Rin08] F. Rindler. Optimal control for nonconvex rate-independent evolution processes. *SIAM J. Control Optim.*, 47(6):2773–2794, 2008.
- [Rin09] F. Rindler. Approximation of rate-independent optimal control problems. *SIAM J. Numer. Anal.*, 47(5):3884–3909, 2009.
- [RSZ09] T. Roubíček, L. Scardia, and C. Zanini. Quasistatic delamination problem. *Contin. Mech. Thermodyn.*, 21:223–235, 2009.
- [Sch08] B. Schmidt. Linear Γ -limits of multiwell energies in nonlinear elasticity theory. *Contin. Mech. Thermodyn.*, 20(6):375–396, 2008.
- [Sch09] B. Schmidt. On the derivation of linear elasticity from atomistic models. *Netw. Heterog. Media*, 4(4):789–812, 2009.
- [Ste08] U. Stefanelli. The Brezis-Ekeland principle for doubly nonlinear equations. *SIAM J. Control Optim.*, 47(3):1615–1642, 2008.
- [Suq81] P.-M. Suquet. Sur les équations de la plasticité: existence et régularité des solutions. *J. Mécanique*, 20:3–39, 1981.

- [SZ11] L. Scardia and C. I. Zeppieri. Gradient theory for plasticity as the Γ -limit of a nonlinear dislocation energy. <http://cvgmt.sns.it/cgi/get.cgi/papers/scazep10/>, 2011.
- [Tim09] A. Timofte. Homogeneization for a nonlinear ferroelastic model. *Asymptot. Anal.*, 61(3-4):177–194, 2009.
- [TM10] M. Thomas and A. Mielke. Damage on nonlinearly elastic materials small strain-existence and regularity results. *ZAMM Z. Angew. Math. Mech.*, 90(2):88–112, 2010.

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