LOWER SEMICONSTINUITY OF $L^\infty$ FUNCTIONALS

E.N. BARRON$^{a,1}$, R.R. JENSEN$^{a,1}$, C.Y. WANG$^{a,b,2}$

$^a$Department of Mathematical & Computer Sciences, Loyola University Chicago, Chicago, IL 60626, USA
$^b$Department of Mathematics, University of Kentucky, Lexington, KY 40506, USA

Received 28 August 2000

ABSTRACT. – We study the lower semicontinuity properties and existence of a minimizer of the functional

$$F(u) = \text{ess sup}_{x \in \Omega} f(x, u(x), Du(x))$$

on $W^{1,\infty}(\Omega; \mathbb{R}^m)$. We introduce the notions of Morrey quasiconvexity, polyquasiconvexity, and rank-one quasiconvexity, all stemming from the notion of quasiconvexity (= convex level sets) of $f$ in the last variable. We also formally derive the Aronsson–Euler equation for such problems.

AMS classification: 49A50; 49A51

Keywords: Lower semicontinuity; Morrey convex; Morrey quasiconvex; Polyquasiconvex; Rank-one quasiconvex

RÉSUMÉ. – On examine les propriétés de semi-continuité inférieure et l’existence du minimiseur de la fonctionnelle

$$F(u) = \text{ess sup}_{x \in \Omega} f(x, u(x), Du(x))$$

sur $W^{1,\infty}(\Omega; \mathbb{R}^m)$. On introduit les idées du quasi-convexité de Morrey, du polyquasi-convexité, et du quasi-convexité du rang-un, qui suivent tous de l’idée de quasi-convexité ( = les ensembles à niveau convexes) de $f$ à la dernière variable. En plus, on en déduit dans les formes l’équation d’Aronsson–Euler pour de tels problèmes.

1. Introduction

The major area of study in calculus of variations in the last thirty years has been the study of variational problems with vector valued functions and the associated necessary

E-mail addresses: enb@math.luc.edu (E.N. Barron), rrj@math.luc.edu (R.R. Jensen), wang@math.luc.edu (C.Y. Wang).

$^1$ Supported in part by grants DMS-9532030 and DMS-9972043 from the National Science Foundation.

$^2$ Supported in part by NSF grant DMS-9970549 and an AMS Centennial Fellowship.
and sufficient conditions for lower semicontinuity of integral functionals. It is our goal to consider this problem for essential supremum functionals.

It is well known that for integral problems these necessary and sufficient conditions involve notions of convexity in some form. This has led to concepts of quasiconvexity, polyconvexity, and rank-one convexity. In this paper we change the terminology slightly to account for multiple uses of the word quasiconvexity. In place of quasiconvex when it relates to vector valued variational problems we use the term Morrey convex in honor of the founder of this condition. Here is the definition of Morrey convexity which is well known (see Dacorogna [9] and the references there) to be a necessary and sufficient for weak \( W^{1,p} \) lower semicontinuity of the integral functional

\[
F(u) = \int_{\Omega} f(Du) \, dx.
\]

**Definition 1.1.** Let \( \mathbb{R}^{nm} \) denote the class of all \( n \times m \) matrices with real entries. A function \( f : \mathbb{R}^{nm} \to \mathbb{R} \) is Morrey convex if for each \( A \in \mathbb{R}^{nm} \)

\[
\frac{1}{|\Omega|} \int_{\Omega} f(A + D\varphi(x)) \, dx \geq f(A),
\]

for each \( \Omega \), a bounded domain in \( \mathbb{R}^n \), and \( \varphi \in W_{0}^{1,\infty}(\Omega; \mathbb{R}^m) \). Equivalently,

\[
f(A) = \min \left\{ \frac{1}{|\Omega|} \int_{\Omega} f(A + D\varphi(x)) \, dx \mid \varphi \in W_{0}^{1,\infty}(\Omega; \mathbb{R}^m) \right\}.
\]

Observe the connection with Jensen’s inequality for convex functions. Indeed, this inequality has been fundamental to the existence theory in variational problems. In Barron, Jensen, Liu [7] we have derived an extended Jensen inequality which is just as fundamental for variational problems in \( L^\infty \). It applies to quasiconvex functions, i.e., functions with convex level sets. In symbols, \( f \) is quasiconvex if \( E_\gamma = \{ x \in \mathbb{R}^n \mid f(x) \leq \gamma \} \) is convex for any \( \gamma \in \mathbb{R} \); equivalently,

\[
f(\lambda x + (1 - \lambda)y) \leq f(x) \vee f(y), \quad \forall x, y \in \mathbb{R}^n, \lambda \in (0, 1).
\]

Here is our extended Jensen inequality and its short proof.

**Theorem 1.2.** Let \( f : \Omega \subset \mathbb{R}^n \to \mathbb{R} \) be lower semicontinuous and quasiconvex and let \( \mu \) be a probability measure on \( \mathbb{R}^n \) supported on \( \Omega \). Let \( \varphi \in L^1(\Omega; \mu) \) be a given function. Then

\[
f \left( \int_{\Omega} \varphi \, d\mu \right) \leq \mu - \text{ess sup}_{x \in \Omega} f(\varphi(x)).
\]

The \( \mu \)-essential supremum means we exclude sets of \( \mu \)-measure zero.

**Proof.** Define \( \gamma = \mu - \text{ess sup}_{x \in \Omega} f(\varphi(x)) \) and \( E_\gamma = \{ q : f(q) \leq \gamma \} \). Then for \( \mu \)-a.e. \( x \in \Omega, \varphi(x) \in E_\gamma \). Since \( f \) is lsc and quasiconvex, \( E_\gamma \) is a closed convex set. Hence, since \( \mu \) is a probability measure, \( \int_{\Omega} \varphi \, d\mu \in E_\gamma \) and the theorem is proved. \( \square \)
Notice that a quasiconvex function may be neither continuous nor even lower semicontinuous.

We now introduce a condition similar to Morrey convexity which we will see is (almost) necessary and sufficient for weak-* lower semicontinuity of functionals of the form

\[ F(u) = F(u, \Omega) = \operatorname{ess sup}_{x \in \Omega} f(Du(x)). \]

**Definition 1.3.** \( f : \mathbb{R}^{nm} \rightarrow \mathbb{R} \) is (weak) Morrey quasiconvex if for each \( A \in \mathbb{R}^{nm} \),

\[ f(A) \leq \operatorname{ess sup}_{x \in Q} f(A + D\phi), \quad \forall \phi \in W^{1,\infty}_0(Q; \mathbb{R}^m). \]

Equivalently,

\[ f(A) = \min \{ \operatorname{ess sup}_{x \in Q} f(A + D\phi) : \phi \in W^{1,\infty}_0(Q; \mathbb{R}^m) \}, \]

where \( Q = [0, 1]^n \subset \mathbb{R}^n \) throughout this paper denotes the standard unit cube.

The space of test functions in the classical definition of Morrey convexity may be replaced by \( \phi \in C_0^\infty(Q; \mathbb{R}^m) \). It is clear that one cannot replace the class of test functions in this definition by \( C_0^\infty \) since we do not have uniform approximation of the derivatives.

The following lemma shows that our definition of Morrey quasiconvexity satisfies the analogue of the quasiconvexity definition in convex analysis, i.e., that the level sets of a quasiconvex function must be convex.

**Lemma 1.4.** \( f \) is Morrey quasiconvex iff \( E_c = \{ A \in \mathbb{R}^{nm} : f(A) \leq c \} \) is Morrey convex for every \( c \in \mathbb{R} \). That is,

\[ \delta(A | E_c) = \begin{cases} 0, & \text{if } A \in E_c, \\ +\infty, & \text{if } A \notin E_c, \end{cases} \]

is a Morrey convex function for every \( c \in \mathbb{R} \).

**Proof.** Suppose that \( \delta(A | E_c) \) is Morrey convex for every \( c \in \mathbb{R} \). If \( f \) is not Morrey quasiconvex at \( A \in \mathbb{R}^{nm} \), there is an \( \varepsilon > 0 \) and \( \phi \in W^{1,\infty}_0(Q; \mathbb{R}^m) \) so that \( f(A) - \varepsilon \geq \operatorname{ess sup}_{x \in Q} f(A + D\phi) \). Choose \( c = f(A) - \varepsilon \). Then \( \delta(A | E_c) = +\infty \). Since \( \delta(A | E_c) \) is Morrey convex, we conclude that \( \delta(A + D\phi | E_c) = +\infty \) on a subset of \( Q \) with positive measure. Hence, \( c \geq \operatorname{ess sup}_{x \in Q} f(A + D\phi) > c \), a contradiction and \( f \) must be Morrey quasiconvex.

Conversely, suppose \( f \) is Morrey quasiconvex at \( A \in \mathbb{R}^{nm} \) and \( c \in \mathbb{R} \) is arbitrary. Suppose that \( f(A) \leq c \). Then \( \delta(A | E_c) = 0 \) and immediately, since \( \delta \geq 0 \), \( \delta(A | E_c) \) is Morrey convex. If \( f(A) > c \) then \( \delta(A | E_c) = +\infty \). If \( \delta(A | E_c) \) is not Morrey convex, there is a \( \phi \in W^{1,\infty}_0(Q; \mathbb{R}^m) \) so that \( \int_Q \delta(A + D\phi | E_c) \, dx = 0 \). But then, \( f(A + D\phi) \leq c \) a.e. on \( Q \), i.e., \( \operatorname{ess sup}_{x \in Q} f(A + D\phi) \leq c < f(A) \), a contradiction to the assumption that \( f \) is Morrey quasiconvex. □

For lower semicontinuity of functionals on \( L^\infty \) Morrey quasiconvexity is the analogue of Morrey convexity, but it turns out that for vector valued problems we need to modify
the notion to weak and strong Morrey quasiconvexity. We refer to the definition given above as the weak version. The strong version permits some play in the test functions \( \varphi \) on the boundary of the domain and this is what we need to get the lower semicontinuity result we are after. In the scalar case, i.e., \( m = 1 \) or \( n = 1 \), weak and strong Morrey quasiconvexity are equivalent. It is an important open problem to determine if they are also equivalent in the vector case. We conjecture that they are not equivalent.

We also introduce the notions of polyquasiconvex and rank-one quasiconvex as generalizations of the classical notions polyconvex and rank-one convex. In the classical case we know that we have the implications

\[
\text{f convex } \Rightarrow \text{ f polyconvex } \Rightarrow \text{ f Morrey convex } \Rightarrow \text{ f rank-one convex.}
\]

It is known that \( f \) Morrey convex does not imply \( f \) is polyconvex. The famous counterexample of Sverak [14] shows that

\[
f \text{ rank-one convex } \nRightarrow f \text{ Morrey convex,
}\]

at least when \( m \geq 3, n \geq 2 \). Obviously the question arises as to whether this can be extended to \( L^\infty \) but counterexamples, which are not easy to come by in the classical cases, are no easier in \( L^\infty \). As is usual in a paper of this type, more questions are raised than are answered but we hope to return to these questions in a future paper. In particular we hope to resolve the relaxation question and the use of Young measures in such relaxations. Excellent references for these and many other considerations are Dacorogna [9] and Pedregal [13].

The main difficulty in dealing with \( L^\infty \) functionals is the fact that we do not have available to us the major tool used in \( L^p \) functionals, namely, the use of piecewise affine functions. Approximation of a \( W^{1,\infty} \) function on a domain \( \Omega \) by piecewise affine functions leaves a piece of small measure left over. In integral problems this portion is controlled since it is a small measure set, but in \( L^\infty \) small measure sets cannot be ignored, and functions on them cannot be controlled easily. Another idea which one might think of is the use of approximating \( L^\infty \) by \( L^p \). In lower semicontinuity considerations this leads to then studying an iterated limit \( \lim_{k \to \infty} \lim_{p \to \infty} \) which there is no reason to believe that the limits can be reversed.

Variational problems in \( L^\infty \) were first studied systematically by Aronsson [1–3]. Then Jensen in [12] considered the uniqueness question for the Aronsson equation arising in the minimization of \( \text{ess sup}_{x \in \Omega} |Du|^2 \) or \( \text{ess sup}_{x \in \Omega} |Du| \). Barron and Ishii [6] initiated the study of optimal control via viscosity solutions in \( L^\infty \) and Barron and Liu [8] studied calculus of variations in \( L^\infty \) in the scalar case from the point of view of relaxation and duality. A survey of the foregoing and many other results is in Barron [5].

Finally, the motivation to consider \( L^\infty \) variational problems is provided by simple examples without simple solutions. A typical vector valued problem arising in elasticity (see for example [9]) developed by Ball [4] is to minimize the integral

\[
I(u) = \int_{\Omega} W(x, Du(x)) + \psi(x, u(x)) \, dx,
\]
where $\Omega$ is the reference configuration of a given elastic material and $u$ is the deformation of the body. Usually it is assumed that $\det(Du(x)) > 0$, $x \in \Omega$. The stored energy of the configuration is measured in the function $W = W(x, Du(x))$ and the function $\psi$ measures the body force per unit volume. It would seem to make sense that one should replace the integral by the essential supremum in certain bodies in which cracks are a primary consideration since in fact cracks occur due to pointwise excessive energy. Pointwise considerations arise in many practical applications including temperature distribution, chemotherapy, risk management, etc., and of course it is a fundamental problem in Chebychev approximation of functions.

2. Morrey quasiconvexity and lower semicontinuity in $L^\infty$

We begin with a precise definition of what we mean by Morrey quasiconvexity. Then we show that this condition is necessary and sufficient for lower semicontinuity.

**DEFINITION 2.1.** – A measurable function $f : \mathbb{R}^{nm} \to \mathbb{R}$ is said to be (strong) Morrey quasiconvex, if for any $\varepsilon > 0$, for any $A \in \mathbb{R}^{nm}$, and any $K > 0$, there exists a $\delta = \delta(\varepsilon, K, A) > 0$ such that if $\varphi \in W^{1,\infty}(Q; \mathbb{R}^m)$ satisfies
\[
\|D\varphi\|_{L^\infty(Q)} \leq K, \quad \max_{x \in \partial Q} |\varphi(x)| \leq \delta,
\]
then,
\[
f(A) \leq \text{ess sup}_{x \in Q} f(A + D\varphi(x)) + \varepsilon. \tag{2.1}
\]

**DEFINITION 2.2.** – A measurable function $f : \mathbb{R}^{nm} \to \mathbb{R}$ is said to be weak Morrey quasiconvex, or $(0,0)$ Morrey quasiconvex, if for any $A \in \mathbb{R}^{nm}$, and $\varphi \in W^{1,\infty}_0(Q; \mathbb{R}^m)$, we have
\[
f(A) \leq \text{ess sup}_{x \in Q} f(A + D\varphi(x)). \tag{2.2}
\]

**Remark 2.3.** – One can easily check from the definitions that if $f : \mathbb{R}^{nm} \to \mathbb{R}$ is Morrey quasiconvex then it is automatically weak Morrey quasiconvex. In Section 3 we prove that for either $n = 1$ or $m = 1$ weak Morrey quasiconvexity also implies Morrey quasiconvexity. However, it is an open question whether Morrey quasiconvexity and weak Morrey quasiconvexity are equivalent for $m, n > 1$.

Throughout this paper *Morrey quasiconvexity* will mean strong Morrey quasiconvexity.

Recall from Definition 1.1 that if a measurable function $f : \mathbb{R}^{nm} \to \mathbb{R}$ is Morrey convex, then for any $A \in \mathbb{R}^{nm}$,
\[
f(A) \leq \frac{1}{|Q|} \int_Q f(A + D\varphi) \, dx, \quad \forall \varphi \in W^{1,\infty}_0(Q; \mathbb{R}^m). \tag{2.3}
\]

Just as a convex function is always quasiconvex, a Morrey convex function with appropriate growth conditions is always Morrey quasiconvex. In fact, we have
**Proposition 2.4.** — Let \( f : \mathbb{R}^{nm} \to \mathbb{R} \) be Morrey convex. For any \( \varepsilon > 0 \) there exists a \( \delta > 0 \), depending only on \( \varepsilon \) and the Lipschitz constant of \( f \) on \( Q \), such that if \( \varphi \in W^{1,\infty}(Q; \mathbb{R}^m) \) satisfies \( \max_{x \in \partial Q} |\varphi(x)| \leq \delta \) then

\[
f(A) \leq \frac{1}{|Q|} \int_Q f(A + D\varphi) \, dx + \varepsilon \leq \operatorname{ess sup}_{x \in Q} f(A + D\varphi(x)) + \varepsilon.
\]

(2.4)

**Proof.** — Let \( \delta > 0 \) be chosen later. Let \( \varphi \in W^{1,\infty}(Q; \mathbb{R}^m) \) with \( \max_{x \in \partial Q} |\varphi(x)| \leq \delta \). Then there exists \( \eta = \eta(\delta, \|D\varphi\|_{L^\infty(Q)}) > 0 \) such that \( |\varphi(y)| \leq 2\delta \) for any \( y = (y_1, \ldots, y_n) \in Q \) with \( |y_i| \geq 1 - \eta \) for some \( 1 \leq i \leq n \). Let \( \xi \in C^1_0(\mathbb{R}^n) \) be such that \( \xi \equiv 1 \) for \( y \in (1 - \eta)Q \), \( \xi \equiv 0 \) for \( y \notin Q \), and \( |D\xi| \leq 4/\eta \). Then the Morrey convexity condition implies

\[
f(A) \leq \frac{1}{|Q|} \int_Q f(A + D(\xi\varphi)) \, dx.
\]

However,

\[
\frac{1}{|Q|} \int_Q f(A + D(\xi\varphi)) \, dx = \frac{1}{|Q|} \int_Q f(A + D\varphi) \, dx + \frac{1}{|Q|} \int_{Q \setminus (1-\eta)Q} (f(A + D(\xi\varphi)) - f(A + D\varphi)) \, dx = I + II.
\]

Since \( f \) is Morrey convex and hence convex in each component variable as well as locally Lipschitz, it follows that \( \|Df\|_{L^\infty(Q)} \leq C \). Therefore,

\[
|II| \leq C \int_{Q \setminus (1-\eta)Q} |D\varphi| + |D\xi||\varphi| \, dx \leq C \left( \|D\varphi\|_{L^\infty(Q)} \eta + \delta \right).
\]

Choose now \( \delta \leq \varepsilon/2C \) and \( \eta = \eta(\varepsilon, \|D\varphi\|_{L^\infty(Q)}) \) sufficiently small so that \( |II| \leq \varepsilon \). Hence,

\[
f(A) \leq I + II \leq \frac{1}{|Q|} \int_Q f(A + D\varphi) \, dx + \varepsilon.
\]

Since

\[
\frac{1}{|Q|} \int_Q f(A + D\varphi) \, dx \leq \operatorname{ess sup}_{x \in Q} f(A + D\varphi(x)) ,
\]

we conclude that

\[
f(A) \leq \frac{1}{|Q|} \int_Q f(A + D\varphi) \, dx + \varepsilon \leq \operatorname{ess sup}_{x \in Q} f(A + D\varphi(x)) + \varepsilon. \quad \square
\]

One key property we need for Morrey quasiconvex functions is the following.
Proposition 2.5. Let \( f : \mathbb{R}^{nm} \to \mathbb{R} \) be Morrey quasiconvex. Let \( \{u_k\} \subset W^{1,\infty}(Q; \mathbb{R}^m) \) be a sequence converging to zero, weak* in \( W^{1,\infty}(Q; \mathbb{R}^m) \). Then,
\[
f(A) \leq \liminf_{k \to \infty} \text{ess sup}_{x \in Q} f(A + Du_k(x)), \quad \forall A \in \mathbb{R}^{nm}.
\] (2.5)

Proof. Since \( u_k \) converges to 0 weak-* in \( W^{1,\infty}(Q; \mathbb{R}^m) \), we have the existence of a finite constant \( K_0 = \sup_k \|Du_k\|_{L^\infty(Q)} \), and \( u_k \to 0 \) uniformly on \( Q \). For any \( \varepsilon > 0 \) and \( A \in \mathbb{R}^{nm} \), it then follows from the definition of Morrey quasiconvexity that there exists a \( \delta = \delta(\varepsilon, K_0, A) \) such that
\[
f(A) \leq \text{ess sup}_{x \in Q} f(A + D\varphi(x)) + \varepsilon,
\] (2.6)
for any \( \varphi \in W^{1,\infty}(Q; \mathbb{R}^m) \) satisfying \( \|D\varphi\|_{L^\infty(Q)} \leq K_0 \) and \( \max_{x \in Q} |\varphi(x)| \leq \delta \). On the other hand, we know that there exists a \( k_0 = k_0(\delta) > 0 \) such that \( \max_{x \in Q} |u_k| \leq \delta \) for all \( k \geq k_0 \). Therefore, we have
\[
f(A) \leq \text{ess sup}_{x \in Q} f(A + Du_k(x)) + \varepsilon, \quad \forall k \geq k_0.
\] This implies
\[
f(A) \leq \liminf_{k \to \infty} \text{ess sup}_{x \in Q} f(A + Du_k(x)) + \varepsilon.
\] (2.7)
Since \( \varepsilon > 0 \) is arbitrary, (2.7) gives (2.5). \[\square\]

Now, we are ready to prove the first main result of our paper. It says that Morrey quasiconvexity gives a sufficient condition for lower semicontinuity.

Theorem 2.6 (Sufficient condition). Let \( f : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^{nm} \to \mathbb{R} \) satisfy:

(i) For any \( (x, s) \in \mathbb{R}^n \times \mathbb{R}^m \), \( f(x, s, \cdot) : \mathbb{R}^{nm} \to \mathbb{R} \) is Morrey quasiconvex;
(ii) There exists a function \( \omega : \mathbb{R}_+ \times \mathbb{R}_+ \to \mathbb{R}_+ \), which is continuous in its first variable and non-decreasing in its second variable, such that
\[
|f(x_1, s_1, A) - f(x_2, s_2, A)| \leq \omega(|x_1 - x_2| + |s_1 - s_2|, |A|),
\] (2.8)
for any \( (x_1, s_1), (x_2, s_2) \in \mathbb{R}^n \times \mathbb{R}^m \) and \( A \in \mathbb{R}^{nm} \).

Then for any bounded domain \( \Omega \subset \mathbb{R}^n \) the functional
\[
F(u, \Omega) = \text{ess sup}_{x \in \Omega} f(x, u(x), Du(x))
\]
is sequentially weak* lower semicontinuous on \( W^{1,\infty}(\Omega; \mathbb{R}^m) \).

Proof. Let \( \varphi_k \) converge to 0 weak* in \( W^{1,\infty}(\Omega; \mathbb{R}^m) \). In particular, we may assume that \( \varphi_k \to 0 \) uniformly on \( \Omega \) and \( D\varphi_k \to 0 \) weak* in \( L^\infty(\Omega, \mathbb{R}^m) \). Set \( u_k = u + \varphi_k \). We need to prove
\[
\text{ess sup}_{x \in \Omega} f(x, u(x), Du(x)) \leq \liminf_{k \to \infty} \text{ess sup}_{x \in \Omega} f(x, u_k(x), Du_k(x)).
\] (2.9)
Let \( \{u_k\} \) denote a subsequence so that
\[
\lim_{k \to \infty} \text{ess sup}_{x \in \Omega} f(x, u_k(x), Du_k(x)) = \liminf_{k \to \infty} \text{ess sup}_{x \in \Omega} f(x, u_k(x), Du_k(x)).
\] (2.10)

Since \( u \) is Lipschitz continuous on \( \Omega \), it follows from Rademacher’s theorem and the Lebesgue density theorem that there exists an \( \Omega_0 \subset \Omega \), with \( \Omega \setminus \Omega_0 = 0 \), such that \( u \) is differentiable at any \( x_0 \in \Omega_0 \) and \( x_0 \) is a Lebesgue point of \( Du \), namely
\[
\lim_{x \to x_0} \frac{|u(x) - u(x_0) - Du(x_0)(x - x_0)|}{|x - x_0|} = 0,
\] (2.11)
and
\[
\lim_{r \downarrow 0} \frac{1}{|Q_r(x_0)|} \int_{Q_r(x_0)} |Du(x) - Du(x_0)| \, dx = 0.
\] (2.12)

Here \( Q_r(x_0) = \{x_0 + rx : x \in Q\} \) denotes the cube with side length \( r \) and center at \( x_0 \).

For \( r > 0 \) small, we define the rescaling maps:
\[
v'_{r, x_0}(x) = \frac{1}{r} (u(x_0 + rx) - u(x_0)) : Q \to \mathbb{R}^m,
\]
and
\[
\phi'_{r, x_0}(x) = \frac{1}{r} (\phi_k(x_0 + rx) - \phi_k(x_0)) : Q \to \mathbb{R}^m.
\]

Then (2.11) and (2.12) imply
\[
\lim_{r \downarrow 0} \max_{x \in Q} |v'_{r, x_0}(x) - Du(x_0)| = 0 \quad \text{and} \quad \lim_{r \downarrow 0} \|Dv'_{r, x_0} - Du(x_0)\|_{L^1(Q)} = 0.
\] (2.13)

Notice also that \( v'_{r, x_0} \) is bounded in \( W^{1,\infty}(Q; \mathbb{R}^m) \). Hence (2.13) implies that \( v'_{r, x_0}(x) \to Du(x_0)x \) weak* in \( W^{1,\infty}(Q; \mathbb{R}^m) \).

For any fixed \( r > 0 \), we observe that
\[
\sup_{k \geq 1} \sup_{x \in Q} \left| \phi'_{r, x_0}(x) \right| \leq \sup_{k \geq 1} \|D\phi_k\|_{L^\infty(\Omega)} < \infty,
\]
and
\[
\sup_{k \geq 1} \sup_{x, y \in Q, x \neq y} \frac{|\phi'_{r, x_0}(x) - \phi'_{r, x_0}(y)|}{|x - y|} \leq \sup_{k \geq 1} \|D\phi_k\|_{L^\infty(\Omega)} < \infty.
\]

Hence, by the Arzela–Ascoli theorem, we may assume that, for any \( r > 0 \) small, \( \phi'_{r, x_0} \) converges to \( \phi \) uniformly on \( Q \). Moreover, since \( D\phi'_{r, x_0}(x) = D\phi_k(x_0 + rx) \) for \( x \in Q \) and \( D\phi_k \to 0 \) weak* in \( L^\infty(\Omega, \mathbb{R}^m) \), we have that, for any \( r > 0 \) small, \( D\phi'_{r, x_0} \to 0 \) weak* in \( L^\infty(Q, \mathbb{R}^m) \). Therefore \( D\phi \equiv 0 \) and \( \phi \equiv \text{constant on } Q \). Since \( \phi'_{r, x_0}(0) = 0 \) we have \( \phi \equiv 0 \) on \( Q \).

In particular, we obtain that, for any \( r > 0 \) small, \( \phi'_{r, x_0} \) converges to 0 weak* in \( W^{1,\infty}(Q; \mathbb{R}^m) \). By the Cauchy diagonal process, we have that for any \( r_i \downarrow 0 \) there exists
\[ k_i \uparrow \infty \text{ such that} \]
\[ u_{x_0}^i(x) \rightarrow D u(x_0)x \quad \text{and} \quad \varphi_{k_i,x_0}^i(x) \rightarrow 0, \quad (2.14) \]
weak* in \( W^{1,\infty}(Q; \mathbb{R}^m) \). Applying Proposition 2.5, we can conclude
\[ f(x_0, u(x_0), D u(x_0)) \leq \lim \inf_{k_i \uparrow \infty} \sup_{x \in Q} f(x_0, u(x_0), D (u_{x_0}^i + \varphi_{k_i,x_0}^i)(x)) \quad (2.15) \]

On the other hand, by (2.8), we have
\[
\begin{align*}
\sup_{x \in Q} f(x, u(x), D u_k(x)) &= \sup_{y \in Q} f(x_0 + r_i y, u(x_0 + r_i y), D u_k(x_0 + r_i y)) \\
&\leq \sup_{y \in Q} f(x_0, u(x_0), D u_k(x_0 + r_i y)) + \max_{y \in Q} \omega(|r_i y| + |u(x_0 + r_i y) - u(x_0)|, |D u_k(x_0 + r_i y)|) \\
&= I + II.
\end{align*}
\]

It is easy to see that
\[ I = \sup_{x \in Q} f(x_0, u(x_0), D (u_{x_0}^i + \varphi_{k_i,x_0}^i)(x)). \]

Since
\[ \max_{x \in Q} |D u_k(x_0 + r_i y)| \leq \|D u_k\|_{L^\infty(\Omega)} \leq C < \infty, \forall k_i, \]
where \( C = \sup_{k_i} \|D u_k\|_{L^\infty(\Omega)} \), we have
\[ |II| \leq \max_{y \in Q} \omega(|r_i y| + |u(x_0 + r_i y) - u(x_0)|, C). \]

Combined with the continuity of \( u \) and \( \omega \) in its first variable, yields
\[ \lim_{r_i \downarrow 0} II = 0. \]

Therefore, we obtain
\[
\begin{align*}
\lim_{k \rightarrow \infty} \sup_{x \in \Omega} f(x, u_k(x), D u_k(x)) &= \lim_{k \rightarrow \infty} \sup_{x \in \Omega} f(x, u_k(x), D u_k(x)) \\
&\geq \lim_{k_i \uparrow \infty} \sup_{x \in \Omega} f(x, u_{k_i}(x), D u_{k_i}(x)) \\
&\geq \lim_{r_i \downarrow 0} \sup_{x \in Q} f(x_0 + r_i y, u(x_0 + r_i y), D u_{k_i}(x_0 + r_i y)) \\
&= \lim_{r_i \downarrow 0} \sup_{y \in Q} f(x_0 + r_i y, u(x_0 + r_i y), D u_{k_i}(x_0 + r_i y))
\end{align*}
\]
condition (2.8)

weak* lower semicontinuous on $W$

On the other hand, since $f$ satisfies (2.8) we have

$$f(x_0, u(x_0), Du(x_0))$$

by (2.15).

Since this holds for any $x_0 \in \Omega_0$ and $|\Omega \setminus \Omega_0| = 0$, we have proved (2.9) and the proof of Theorem 2.6 is complete. □

Now we prove that Morrey quasiconvexity is also a necessary condition for the sequential weak* lower semicontinuity of the functional $F(u, \Omega)$ on $W^{1,\infty}(\Omega; \mathbb{R}^m)$.

**THEOREM 2.7 (Necessary condition).** Let $f : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^{mn} \to \mathbb{R}$ satisfy the condition (2.8). For any bounded $\Omega \subset \mathbb{R}^n$, let $F(u, \Omega) = \text{ess sup}_{x \in \Omega} f(x, u(x), Du(x))$.

Assume that $F(\cdot, \Omega)$ is sequentially weak* lower semicontinuous on $W^{1,\infty}(\Omega; \mathbb{R}^m)$. Then $p \mapsto f(x, u, p)$ is Morrey quasiconvex for any $(x, u) \in \mathbb{R}^n \times \mathbb{R}^m$.

To prove Theorem 2.7 we first need the following lemma. The second part of this lemma exhibits the importance of the extended Jensen inequality.

**LEMMA 2.8.** Let $f : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^{mn} \to \mathbb{R}$ satisfy (2.8). If $F(\cdot, \Omega)$ is sequentially weak* lower semicontinuous on $W^{1,\infty}(\Omega; \mathbb{R}^m)$, then

(i) For any $(x_0, s_0) \in \mathbb{R}^n \times \mathbb{R}^m$, $f(x_0, s_0, \cdot) : \mathbb{R}^{mn} \to \mathbb{R}$ is lower semicontinuous.

(ii) For any $(x_0, s_0) \in \mathbb{R}^n \times \mathbb{R}^m$, we have

$$f\left(x_0, s_0, \frac{1}{|Q|} \int_Q Du(x) \, dx\right) \leq \text{ess sup}_{x \in Q} f(x_0, s_0, Du(x)) \quad (2.16)$$

for any $u \in W^{1,\infty}(Q; \mathbb{R}^m)$ with $Du$ $Q$-periodic.

(iii) For any $(x_0, s_0) \in \mathbb{R}^n \times \mathbb{R}^m$, $f(x_0, s_0, \cdot) : \mathbb{R}^{mn} \to \mathbb{R}$ satisfies the weak Morrey quasiconvexity property:

$$f(x_0, s_0, A) = \inf_{\varphi \in W^{1,\infty}_0(Q; \mathbb{R}^m)} \{\text{ess sup}_{x \in Q} f(x_0, s_0, A + D\varphi(x)) : \varphi \in W^{1,\infty}_0(Q; \mathbb{R}^m)\}. \quad (2.17)$$

**Proof.** (i) For $(x_0, s_0) \in \mathbb{R}^n \times \mathbb{R}^m$. Let $\{A_j\} \subset \mathbb{R}^{mn}$ satisfy $A_j \to A$. Then $u_j(x) = s_0 + A_j(x - x_0)$ converges to $u(x) = s_0 + A(x - x_0)$ in $W^{1,\infty}(B_r(x_0); \mathbb{R}^m)$ for any $r > 0$. Hence we have

$$\text{ess sup}_{x \in B_r(x_0)} f(x, u(x), Du(x)) = \text{ess sup}_{x \in B_r(x_0)} f(x, s_0 + A(x - x_0), A)$$

$$\leq \liminf_{j \to \infty} \text{ess sup}_{x \in B_r(x_0)} f(x, u_j(x), Du_j(x))$$

$$= \liminf_{j \to \infty} \text{ess sup}_{x \in B_r(x_0)} f(x, s_0 + A_j(x - x_0), A_j). \quad (2.18)$$

On the other hand, since $f$ satisfies (2.8) we have

$$\lim_{r \to 0} \text{ess sup}_{x \in B_r(x_0)} f(x, s_0 + A(x - x_0), A) = f(x_0, s_0, A),$$

and

$$\lim_{r \to 0} \text{ess sup}_{x \in B_r(x_0)} f(x, s_0 + A_j(x - x_0), A_j) = f(x_0, s_0, A_j),$$

hence

$$\lim_{r \to 0} \text{ess sup}_{x \in B_r(x_0)} f(x, s_0 + A(x - x_0), A) = f(x_0, s_0, A),$$
uniformly in $j$. Hence, sending $r$ to zero, (2.18) implies

$$f(x_0, s_0, A) \leq \lim_{j \to \infty} f(x_0, s_0, A_j).$$

(ii) For $(x_0, s_0) \in \mathbb{R}^n \times \mathbb{R}^m$. We first extend $u \in W^{1,\infty}(Q; \mathbb{R}^m)$ to $\mathbb{R}^n$ with $Du$ as a $Q$-periodic function. Define $u_j(x) = u((x - x_0))/j + s_0: \mathbb{R}^n \to \mathbb{R}^m$. Then we have

$$u_j(x) \to s_0 + \left(\frac{1}{|Q|} \int_Q Du \, dx\right)(x - x_0),$$

weak* in $W^{1,\infty}(B_r(x_0); \mathbb{R}^m)$, for any $r > 0$. In particular, $Du_j \to \frac{1}{|Q|} \int_Q Du \, dx$ weak* in $L^\infty(B_r(x_0), \mathbb{R}^m)$. Hence we have

$$\begin{aligned}
\text{ess sup}_{x \in B_r(x_0)} f(x_0, s_0 + \left(\frac{1}{|Q|} \int_Q Du \, dx\right)(x - x_0), & = \text{ess sup}_{x \in B_r(x_0)} f(x, u_j(x), Du_j(x)) \\
& = \text{ess sup}_{x \in B_r(x_0)} f\left(x, s_0 + \frac{u(j(x - x_0))}{j}, Du\left(j(x - x_0)\right)\right). \\
& = \text{ess sup}_{x \in Q} f\left(x_0, s_0 + \frac{u(0)}{j}, Du\left(j(x - x_0)\right)\right),
\end{aligned} \tag{2.19}$$

Since $f$ satisfies (2.8) we know, setting $A = \frac{1}{|Q|} \int_Q Du \, dx$

$$\lim_{r \to 0} \text{ess sup}_{x \in B_r(x_0)} f(x, s_0 + A(x - x_0), A) = f(x_0, s_0, A),$$

and

$$\lim_{r \to 0} \text{ess sup}_{x \in B_r(x_0)} f\left(x_0, s_0 + \frac{u(0)}{j}, Du\left(j(x - x_0)\right)\right) = \text{ess sup}_{x \in Q} f\left(x_0, s_0, Du(x)\right).$$

uniformly in $j$. Here we have used the fact that

$$\lim_{x \to x_0} \frac{|u(j(x - x_0)) - u(0)|}{j} = 0.$$

On the other hand, since $Du$ is $Q$-periodic we have

$$\lim_{j \to \infty} \text{ess sup}_{x \in B_r(x_0)} f\left(x_0, s_0 + \frac{u(0)}{j}, Du\left(j(x - x_0)\right)\right) = \text{ess sup}_{x \in Q} f(x_0, s_0, Du(x)).$$

Putting these together and sending $r$ to zero in (2.19), we obtain

$$f\left(x_0, s_0, \frac{1}{|Q|} \int_Q Du \, dx\right) \leq \text{ess sup}_{x \in Q} f(x_0, s_0, Du(x)).$$
Observe that if we were to assume the condition \( f(x_0, s_0, p) = f(x_0, s_0, -p) \) we could drop the assumption that \( Du \) is \( Q \)-periodic.

(iii) Notice we can rewrite (2.16) as

\[
\begin{align*}
f(x_0, s_0, A) &= \inf \left\{ \operatorname{ess sup}_{y \in \partial Q} f(x_0, s_0, D\varphi(y)) : \varphi \in W^{1, \infty}(\mathbb{R}^n; \mathbb{R}^m), \\
D\varphi & \text{ is } Q\text{-periodic,} \quad \frac{1}{|Q|} \int_Q D\varphi \, dx = A \right\} \\
&= \inf \left\{ \operatorname{ess sup}_{y \in \partial Q} f(x_0, s_0, A + D\psi(y)) : \psi \in W^{1, \infty}_0(Q; \mathbb{R}^m) \right\}. \quad (2.20)
\end{align*}
\]

In fact, given \( \psi \in W^{1, \infty}_0(Q; \mathbb{R}^m) \) set \( \varphi(y) = Ay + \psi(y) \). This shows the first infimum in (2.20) is not greater than the second. For the reverse, given any \( \varphi \in W^{1, \infty}(\mathbb{R}^n; \mathbb{R}^m) \) with \( D\varphi \) \( Q \)-periodic and \( \frac{1}{|Q|} \int_Q D\varphi \, dx = A \), take \( \psi \equiv 0 \). Then, by (ii), we have

\[
\begin{align*}
\inf \left\{ \operatorname{ess sup}_{y \in \partial Q} f(x_0, s_0, A + D\psi(y)) : \psi \in W^{1, \infty}_0(Q; \mathbb{R}^m) \right\} \\
&\leq f(x_0, s_0, A) \leq \operatorname{ess sup}_{y \in \partial Q} f(x_0, s_0, D\varphi(y)).
\end{align*}
\]

This shows that the second infimum in (2.20) is not greater than the first and hence they are equal. This gives the weak Morrey quasiconvexity of \( f \) in its last variable. \( \square \)

Now we can return to the proof of Theorem 2.7.

Proof of Theorem 2.7. – We prove it by contradiction. Suppose that \( f \) is not Morrey quasiconvex in its last variable. Then there exist \( (x_0, s_0) \in \mathbb{R}^n \times \mathbb{R}^m, \varepsilon_0 > 0, K_0 > 0, A_0 \in \mathbb{R}^{nm} \), and sequences \( \{\varphi_k\} \subset W^{1, \infty}(Q; \mathbb{R}^m) \) such that

\[
\begin{align*}
\sup_k \|D\varphi_k\|_{L^\infty(Q)} &\leq K_0, \\
\max_{x \in \partial Q} |\varphi_k(x)| &= \delta_k \to 0 \quad \text{as } k \to \infty, \quad (2.21)
\end{align*}
\]

but

\[
f(x_0, s_0, A_0) > \operatorname{ess sup}_{x \in \partial Q} f(x_0, s_0, A_0 + D\varphi_k(x)) + \varepsilon_0, \quad (2.22)
\]

for all \( k \geq 1 \). It follows from (2.21) that we may assume that there exists a \( \varphi \in W^{1, \infty}_0(Q; \mathbb{R}^m) \) such that \( \varphi_k \to \varphi \) weak* in \( W^{1, \infty}(Q; \mathbb{R}^m) \). For any \( r > 0 \), we see that

\[
s_0 + A_0(x - x_0) + r\varphi_k \left( \frac{x - x_0}{r} \right) \to s_0 + A_0(x - x_0) + r\varphi \left( \frac{x - x_0}{r} \right),
\]

weak* in \( W^{1, \infty}(Q_r(x_0); \mathbb{R}^m) \), as \( k \to \infty \). Since \( F(\cdot, Q_r(x_0)) \) is sequentially weak* lower semicontinuous on \( W^{1, \infty} \), we have

\[
\begin{align*}
\operatorname{ess sup}_{y \in \partial Q} f(x_0 + ry, s_0 + rA_0y + r\varphi(y), A_0 + D\varphi(y)) \\
&= \operatorname{ess sup}_{x \in Q_r(x_0)} f \left( x, s_0 + A_0(x - x_0) + r\varphi \left( \frac{x - x_0}{r} \right), A_0 + D\varphi \left( \frac{x - x_0}{r} \right) \right)
\end{align*}
\]
\[ \leq \lim_{k \to \infty} \inf \sup_{x \in Q_{r}(x_0)} f\left( x, s_0 + A_0(x - x_0) + r \phi_k\left( \frac{x - x_0}{r} \right), A_0 + D\phi_k\left( \frac{x - x_0}{r} \right) \right) \]

\[ = \lim_{k \to \infty} \inf \sup_{y \in Q} f\left( x_0 + r y, s_0 + r A_0 y + r \phi_k(y), A_0 + D\phi_k(y) \right). \]

Notice that

\[ \lim_{r \downarrow 0} \max_{y \in Q} |x_0 + r y - x_0| = 0, \]

\[ \lim_{r \downarrow 0} \max_{y \in Q} |s_0 + r A_0 y + r \phi(y) - s_0| = 0, \]

and

\[ \lim_{r \downarrow 0} \max_{k \to \infty} \max_{y \in Q} |s_0 + r A_0 y + r \phi_k(y) - s_0| = 0. \]

Since \( f \) satisfies (ii) of Theorem 2.6, we have, by sending \( r \) to zero, \( \inf \sup_{y \in Q} f\left( x_0, s_0, A_0 + D\phi(y) \right) \leq \lim_{k \to \infty} \inf \sup_{y \in Q} f\left( x_0, s_0, A_0 + D\phi_k(y) \right). \) (2.23)

This, combined with (2.22), implies

\[ \inf \sup_{y \in Q} f\left( x_0, s_0, A_0 + D\phi(y) \right) + \varepsilon_0 < f(x_0, s_0, A_0). \] (2.24)

On the other hand, since \( \phi \in W^{1,\infty}(Q; \mathbb{R}^m) \), it follows from (iii) of Lemma 2.8 that

\[ f(x_0, s_0, A_0) \leq \inf \sup_{y \in Q} f\left( x_0, s_0, A_0 + D\phi(y) \right). \]

This contradicts (2.24). The proof is complete. \( \square \)

We finish this section with an existence theorem for minimizing problems in \( L^\infty \).

**Theorem 2.9.** – If, in addition to the conditions in Theorem 2.6, let \( f : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^{nm} \to \mathbb{R} \) satisfy the following coercivity condition:

\[ f(x, s, A) \geq C_1 |A|^p - C_2, \quad \forall (x, s, A) \in \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^{nm} \] (2.25)

for some \( C_1 > 0, C_2 > 0, \) and \( p > 0. \) Then for any bounded domain \( \Omega \subset \mathbb{R}^n \) and \( \psi \in W^{1,\infty}(\Omega; \mathbb{R}^m) \) there exists at least one function \( u \in W^{1,\infty}(\Omega; \mathbb{R}^m) \), with \( u|_{\partial \Omega} = \psi|_{\partial \Omega} \), so that

\[ \inf_{x \in \Omega} \sup_{s \in \Omega} f(x, s, Du(x)) \]

\[ = \inf \{ \sup_{x \in \Omega} f(x, v(x), Dv(x)) : v \in W^{1,\infty}(\Omega; \mathbb{R}^m), v|_{\partial \Omega} = \psi|_{\partial \Omega} \}. \]

**Proof.** – First notice that

\[ c \equiv \inf_{x \in \Omega} \sup_{x \in \Omega} f(x, \psi(x), D\psi(x)) : v \in W^{1,\infty}(\Omega; \mathbb{R}^m), v|_{\partial \Omega} = \psi|_{\partial \Omega} \]

\[ \leq \sup_{x \in \Omega} f(x, \psi(x), D\psi(x)) < \infty. \]
Moreover, \( c \geq -C_2 > -\infty \).

Let \( \{ u_k \} \subset W^{1,\infty}(\Omega; \mathbb{R}^m) \) be a minimizing sequence with \( u_k|_{\partial \Omega} = \psi|_{\partial \Omega} \), and

\[
\lim_{k \to \infty} \text{ess sup}_{x \in \Omega} f(x, u_k(x), Du_k(x)) = c.
\]

It follows from the coercivity condition (2.25) that \( \| Du_k \|_{L^\infty(\Omega)} \) is bounded. By the Poincare inequality we see that \( \| u_k \| \leq \| \psi \| + \| Du_k \| \) in the \( L^\infty(\Omega) \) norm and so \( \{ u_k \} \) is bounded in \( W^{1,\infty}(\Omega; \mathbb{R}^m) \). Therefore, we may assume that there exists \( u \in W^{1,\infty}(\Omega; \mathbb{R}^m) \) with \( u|_{\partial \Omega} = \psi|_{\partial \Omega} \) so that \( u_k \rightharpoonup u \) weakly in \( W^{1,\infty}(\Omega; \mathbb{R}^m) \). It then follows from Theorem 2.6 that \( u \) is a minimizer and \( \text{ess sup}_{x \in \Omega} f(x, u(x), Du(x)) = c \).

\[\blacksquare\]

**Remark 2.10.** – The coercivity condition of the theorem is essential for the existence of a minimizer. Indeed, consider \( F(u) = \text{ess sup}_{x \in [0, 1]} |x u'(x)| \), with \( u(0) = 1, u(1) = 0 \). Clearly this is not coercive. Consider the sequence

\[
u_n(x) = \begin{cases} 1, & \text{if } 0 \leq x \leq 1/n, \\ -\log x / \log n, & \text{if } 1/n \leq x \leq 1. \end{cases}
\]

Then \( \nu_n \in W^{1,\infty}([0, 1]) \) and

\[
x \nu_n'(x) = \begin{cases} 0, & \text{if } 0 \leq x \leq 1/n, \\ -1/\log n, & \text{if } 1/n \leq x \leq 1. \end{cases}
\]

Hence \( F(\nu_n) = 1/\log n \to 0 \). The infimum of \( F \) is therefore zero, but clearly no Lipschitz function assuming the boundary data can give \( F(u) = 0 \).

On the other hand if we consider instead \( F(u) = \text{ess sup}_{x \in [0, 1]} |u'(x)| \) with \( u(0) = 1, u(1) = 0 \) there is a unique minimizer and it is \( u^*(x) = 1 - x \). Indeed, \( u(1) - u(0) = \int_0^1 u'(x) \, dx \) implies that \( F(u) \geq 1 \) for any Lipschitz \( u \) with \( u(0) = 1, u(1) = 0 \), and \( F(u^*) = 1 \). The uniqueness of the minimizer follows from the fact that

\[
\text{ess sup}_{x \in [x_0, x_1]} |u^*(x)| = 1 \quad \text{for any } 0 \leq x_0 < x_1 \leq 1.
\]

This is Theorem 1 of [1].

**Remark 2.11.** – This theorem establishes the existence of a minimizer but not an absolute minimizer, i.e., a function which minimizes \( F \) on any subdomain. This is what we need to use the Aronsson–Euler equation derived in the last section. In a companion paper *The Euler equation and absolute minimizers of \( L^\infty \) functionals* (to appear in Archives Rat. Mech. Anal.), we do establish the existence of an absolute minimizer for problems with \( u : \mathbb{R}^n \to \mathbb{R} \).

3. Various classes of quasiconvex functions

In this section, we introduce various classes of functions, which are natural extensions to \( L^\infty \) of the well-known concepts of convexity, polyconvexity, Morrey convexity, and rank one convexity. For convenience we rewrite the definition of quasiconvexity.
DEFINITION 3.1 (Quasiconvexity). – A measurable function $f : \mathbb{R}^{nm} \to \mathbb{R}$ is called quasiconvex, if
\[
f(tA + (1-t)B) \leq \max\{f(A), f(B)\}, \quad \forall A, B \in \mathbb{R}^{nm}, \quad 0 \leq t \leq 1.
\] (3.1)

Remark 3.2. – Is every quasiconvex function Morrey convex? Define $f(M) = 0$ for $|M| < 1$ and $f(M) = 2$ otherwise. Then $f$ is quasiconvex, but not continuous. Therefore $f$ is not Morrey convex (since every Morrey convex function must be locally Lipschitz). Quasiconvex or even Morrey quasiconvex functions need not be continuous.

We first prove that the stronger and easier to check condition of quasiconvexity is enough for weak* lower semicontinuity in $W^{1, \infty}$. We restrict ourselves to the simpler case $f = f(Du)$, with the extension to $f(x, u, Du)$ causing only minor technical difficulties.

THEOREM 3.3. – Let $f : \mathbb{R}^{nm} \to \mathbb{R}$ be quasiconvex and lower semicontinuous. Then, for any bounded domain $\Omega \subset \mathbb{R}^n$, $F(u, \Omega) = \text{ess sup}_{x \in \Omega} f(Du(x))$ is sequentially weak* lower semicontinuous on $W^{1, \infty}$.\)

Proof. – For any $r \in \mathbb{R}$, let $E_r = \{A \in \mathbb{R}^{nm} : f(A) \leq r\}$. Then since $f$ is lower semicontinuous and quasiconvex $E_r$ is a closed convex set. Let $d(\cdot, E_r) : \mathbb{R}^{nm} \to \mathbb{R}$ denote the distance function to $E_r$, i.e.,
\[
d(A, E_r) = \inf_{B \in E_r} |A - B| = \inf_{B \in \mathbb{R}^{nm}} \delta(B | E_r) + |A - B|,
\]
where $| \cdot |$ is a norm on $\mathbb{R}^{nm}$. Then since $E_r$ is closed and convex, $d(\cdot, E_r)$ is Lipschitz continuous and convex. Hence it is well-known (see, [9] for example) that
\[
G(u, \Omega) = \int_{\Omega} d(Du(x), E_r) \, dx
\]
is sequentially weak* lower semicontinuous on $W^{1, \infty}$. Thus, if $u_k$ converges to $u \in W^{1, \infty}$ weak* in $W^{1, \infty}$, we have
\[
\int_{\Omega} d(Du(x), E_r) \, dx \leq \liminf_{k \to \infty} \int_{\Omega} d(Du_k(x), E_r) \, dx.
\] (3.2)

Let
\[
r_0 = \liminf_{k} \text{ess sup}_{x \in \Omega} f(Du_k(x)) = \lim_{i \to \infty} \text{ess sup}_{x \in \Omega} f(Du_i(x)).
\]
Then for any $\varepsilon > 0$, there exists $i_0 = i_0(\varepsilon) > 0$ such that for $i \geq i_0$
\[
f(Du_k(x)) \in E_{r_0 + \varepsilon}, \quad \text{for a.e. } x \in \Omega,
\]
so that
\[
d(Du_k(x), E_{r_0 + \varepsilon}) = 0, \quad \text{a.e. } x \in \Omega.
\]
Hence (3.2) implies
\[ \int_{\Omega} d(Du(x), E_{r_0+\varepsilon}) \, dx = 0. \]
This implies
\[ f(Du(x)) \leq r_0 + \varepsilon \quad \text{a.e. } x \in \Omega. \]
Since \( \varepsilon > 0 \) is arbitrary, this gives
\[ \text{ess sup}_{x \in \Omega} f(Du(x)) \leq \liminf_{k} \text{ess sup}_{x \in \Omega} f(Du_k(x)), \]
and completes the proof. \( \square \)

The proof of this theorem can be used to extend a result of Ioffe [10] to \( L^\infty \) in the scalar case. In particular, we will consider
\[ F(u, v) = \mu - \text{ess sup}_{x \in \Omega} f(x, u(x), v(x)), \]
where \((\Omega, A, \mu)\) is a measure space with \( \mu \) nonnegative and finite and \( f: \Omega \times \mathbb{R}^m \times \mathbb{R}^n \rightarrow [0, \infty) \) is \( A \times B_m \times B_n \)-measurable, where \( B_m \) denotes the Borel subsets of \( \mathbb{R}^m \).

**Theorem 3.4.** – Assume that for \( \mu \)-a.e. \( x \in \Omega \) \( f(x, \cdot, \cdot) \) is lower semicontinuous on \( \mathbb{R}^m \times \mathbb{R}^n \) and for every \( u \in \mathbb{R}^m \) \( f(x, u, \cdot) \) is quasiconvex on \( \mathbb{R}^n \). Then the functional in (3.3) is sequentially lower semicontinuous on \( L^\infty_{\mu}(\Omega; \mathbb{R}^m) \times L^\infty_{\mu}(\Omega; \mathbb{R}^n) \) using the strong topology on \( L^\infty_{\mu}(\Omega; \mathbb{R}^m) \) and the weak* topology on \( L^\infty_{\mu}(\Omega; \mathbb{R}^n) \).

**Proof.** – The proof is similar to that of the previous theorem but here we can use the indicator function
\[ \delta(x, u(x), v(x) \mid E_r) \quad \text{with } E_r = \{(y, \xi, \eta) \in \Omega \times \mathbb{R}^m \times \mathbb{R}^n \mid f(y, \xi, \eta) \leq r\}. \]
With our hypotheses on \( f \) the indicator function satisfies all of the hypotheses of Ioffe’s theorem [10] and so we can complete the proof as before using the integral functional
\[ G(x, u(x), v(x)) = \int_{\Omega} \delta(x, u(x), v(x) \mid E_r) \, dx. \]
The proof is simplified by use of the indicator function which can be used due to the fact that Ioffe’s theorem permits extended real valued integrands. \( \square \)

Naturally, this theorem includes as a special case the variational problem \( F(u) = \mu - \text{ess sup}_{x \in \Omega} f(x, u(x), u'(x)) \).

Now we turn to an extension of the idea of a polyconvex function.

**Definition 3.5 (Polyquasiconvexity).** – A measurable function \( f: \mathbb{R}^{nm} \rightarrow \mathbb{R} \) is called polyquasiconvex if there exists a quasiconvex function \( g: \mathbb{R}^{c(n,m)} \rightarrow \mathbb{R} \) such that
\( f(A) = g(T(A)) \), where \( c(n, m) \) is given by

\[
c(n, m) = \min(n, m) \sum_{s=1}^{\min(n, m)} \frac{m! n! s! (m-s)! (n-s)!}{s! (m-s)! (n-s)!}
\]

and \( T(A): \mathbb{R}^{nm} \to \mathbb{R}^{c(n, m)} \) is the map consisting of \( A \) and all of its \( s \times s \) minors for \( s \leq \min(n, m) \).

A polyconvex function satisfies the same definition except that the function \( g \) must be convex, and not just quasiconvex. These types of functions are important in variational problems arising in elasticity.

It is clear from the definition that every quasiconvex function is polyquasiconvex and any polyconvex function is also polyquasiconvex.

**Proposition 3.6.** Let \( f: \mathbb{R}^{nm} \to \mathbb{R} \) be polyquasiconvex and lower semicontinuous. Then, for any bounded domain \( \Omega \subset \mathbb{R}^{n} \), \( F(u, \Omega) = \text{ess sup}_{x \in \Omega} f(Du(x)) \) is sequentially weak* lower semicontinuous on \( W^{1,\infty}(\Omega; \mathbb{R}^{m}) \).

**Proof.** Let \( g: \mathbb{R}^{c(n, m)} \to \mathbb{R} \) be quasiconvex so that \( f(A) = g(T(A)) \). Assume that \( u_k \) converges to \( u \) weak* in \( W^{1,\infty}(\Omega; \mathbb{R}^{m}) \). It is well-known (see [9] for example) that \( T(Du_k) \to T(Du) \), weak* in \( W^{1,\infty}(\Omega; \mathbb{R}^{m}) \).

Now we can apply the same argument of Proposition 3.3 to show that

\[
\text{ess sup}_{x \in \Omega} g(T(Du(x))) \leq \liminf_{k \to \infty} \text{ess sup}_{x \in \Omega} g(T(Du_k(x))). \tag{3.4}
\]

This finishes the proof. \( \square \)

The last notion of convexity we extend is rank one convexity:

**Definition 3.7 (Rank one quasiconvexity).** A measurable function \( f: \mathbb{R}^{nm} \to \mathbb{R} \) is rank one quasiconvex if (3.1) holds for any \( A, B \in \mathbb{R}^{nm} \) with \( \text{rank}(A - B) \leq 1 \).

Rank one convexity means \( f(tA + (1 - t)B) \leq tf(A) + (1 - t)f(B) \), for rank \( (A - B) \leq 1 \).

It is clear that any quasiconvex function is rank one quasiconvex and any rank one convex function is also rank one quasiconvex.

**Proposition 3.8.** Let \( f: \mathbb{R}^{nm} \to \mathbb{R} \) satisfy the weak Morrey quasiconvexity property:

\[
f(A) \leq \text{ess sup}_{x \in Q} f(A + D\varphi(x)), \quad \text{for any } A \in \mathbb{R}^{nm} \text{ and } \varphi \in W^{1,\infty}_0(Q; \mathbb{R}^{m}).
\]

Then \( f \) is rank one quasiconvex.

**Proof.** A result in Dacorogna [9] asserts that for any \( A, B \in \mathbb{R}^{nm} \) with \( \text{rank}(A - B) \leq 1 \), any \( \varepsilon > 0 \), and \( t \in [0, 1] \), there exist two subdomains \( Q_1, Q_2 \), with \( Q_1 \cap Q_2 = \emptyset \), and
\[ \varphi_\varepsilon \in W^{1,\infty}_0(Q; \mathbb{R}^m) \text{ such that} \]

\[ \|Q^1_\varepsilon - tQ\| \leq \varepsilon, \quad \|Q^2_\varepsilon - (1-t)Q\| \leq \varepsilon, \]

\[ D\varphi_\varepsilon = \begin{cases} (1-t)(A - B) & \text{in } Q^1_\varepsilon, \\ -t(A - B) & \text{in } Q^2_\varepsilon, \end{cases} \]

and

\[ \|D\varphi_\varepsilon\|_{L^\infty(Q)} \leq K(A, B) < \infty. \]

Moreover, it follows from the construction in [9] that \( Q^1_\varepsilon \) and \( Q^2_\varepsilon \) are increasing as \( \varepsilon \) decreases. Letting \( \varepsilon \downarrow 0 \), we may assume that \( Q_i = \lim_{\varepsilon \downarrow 0} Q^i_\varepsilon \), \( i = 1, 2 \), exists, and there exists a \( \varphi_0 \in W^{1,\infty}_0(Q; \mathbb{R}^m) \) such that \( D\varphi_\varepsilon \to D\varphi_0 \) weak* in \( L^\infty(Q, \mathbb{R}^m) \).

Furthermore, we know that the interiors of \( Q_1 \) and \( Q_2 \) have empty intersection, \( |Q_1| = t|Q|, \ |Q_2| = (1-t)|Q|, \ D\varphi_0 = (1-t)(A - B) \) in \( Q_1 \), and \( D\varphi_0 = -t(A - B) \) in \( Q_2 \). Notice also that \( |Q_1 \cup Q_2| = |Q| \).

Now we apply the weak Morrey quasiconvexity of \( f \) to obtain

\[ f(tA + (1-t)B) \leq \esssup_{x \in Q} f(tA + (1-t)B + D\varphi_0(x)) \]

\[ = \esssup_{x \in Q_1 \cup Q_2} f(tA + (1-t)B + D\varphi_0(x)) \]

\[ = \max \{\esssup_{x \in Q_1} f(tA + (1-t)B + D\varphi_0(x)), \esssup_{x \in Q_2} f(tA + (1-t)B + D\varphi_0(x))\} \]

\[ = \max \{ f(A), f(B) \}. \]

This shows that \( f \) is rank one quasiconvex. \( \square \)

Summarizing our results we have proved the following corollary.

**Corollary 3.9.** — Let \( f : \mathbb{R}^{nm} \to \mathbb{R} \) lower semicontinuous be given. Then the following holds:

1. If \( f \) is quasiconvex, then \( f \) is polyquasiconvex.
2. If \( f \) is polyquasiconvex, then \( f \) is Morrey quasiconvex.
3. If \( f \) is Morrey quasiconvex, then \( f \) is weak Morrey quasiconvex.
4. If \( f \) is weak Morrey quasiconvex, then \( f \) is rank one quasiconvex.
5. If either \( n = 1 \) or \( m = 1 \), then all these notions are equivalent.

Thus,

\[ f \text{ quasiconvex } \Rightarrow f \text{ polyquasiconvex } \Rightarrow \]

\[ f \text{ Morrey quasiconvex } \Rightarrow f \text{ weak Morrey quasiconvex } \Rightarrow f \text{ rank one quasiconvex}. \]

Given an arbitrary function \( f : \mathbb{R}^{nm} \to \mathbb{R} \) we could define the greatest Morrey quasiconvex minorant, greatest polyquasiconvex minorant, etc., as the relaxation of \( f \). These considerations will be addressed later.
4. Convex properties do not carry over

Lemma 1.4 of the introduction is useful primarily in that it gives us a tool to prove theorems about Morrey quasiconvex functions and functionals in $L^\infty$ by reducing them to Morrey convex functions and associated integral functionals. Unfortunately, this generally does not work in the vector valued case because most of the results in that case need a growth condition on the integrand, which, of course, the indicator function does not satisfy.

One might think that the way to get around the extended real valued problem is to take the inf convolution of the indicator function. This procedure then will satisfy the growth conditions, but then a new problem arises in the vector valued case. While the inf convolution of a convex function is convex, it is not true, as we will verify in this section, that the inf convolution of a Morrey convex function is Morrey convex. Hence, for vector valued problems we would convert the Morrey convex function $\delta(A \mid E_c)$ into a function which is not Morrey convex and so lower semicontinuity theorems would not apply.

Recall that for a given function $f : \mathbb{R}^{nm} \to \mathbb{R}$, say lower semicontinuous and bounded from below, the $\varepsilon$-inf convolution of $f$ is defined by

$$f_\varepsilon(A) = \inf_{B \in \mathbb{R}^{nm}} \left\{ f(B) + \frac{1}{2\varepsilon} |A - B|^2 \right\}.$$ 

It is well known that if $f$ is convex, then $f_\varepsilon$ is convex for any $\varepsilon > 0$. Furthermore, if $f$ is quasiconvex, i.e., has convex level sets, then $f_\varepsilon$ is also quasiconvex. In the following example we will show that if $f$ is Morrey convex, or even polyconvex, then $f_\varepsilon$ may fail to be even rank one convex.

Define $f : \mathbb{R}^{2 \times 2} \to \mathbb{R}$ by $f(A) = \text{det}(A)$. Set $A = (a_{ij}), \ B = (b_{ij}), \ i, j = 1, 2$. We compute $f_\varepsilon$ from

$$f_\varepsilon(A) = \inf_{B} \left( b_{11}b_{22} - b_{12}b_{21} + \frac{1}{2\varepsilon} \left[ \sum_{i,j=1}^{2} (a_{ij} - b_{ij})^2 \right] \right).$$ 

The necessary conditions for a minimum point become the system of equations

$$b_{22} - \frac{a_{11} - b_{11}}{\varepsilon} = 0, \quad b_{11} - \frac{a_{22} - b_{22}}{\varepsilon} = 0,$$

$$-b_{21} - \frac{a_{12} - b_{12}}{\varepsilon} = 0, \quad -b_{12} - \frac{a_{21} - b_{21}}{\varepsilon} = 0.$$ 

Solving these equations we obtain

$$b_{11} = \frac{1}{\alpha} (a_{11} - \varepsilon \ a_{22}), \quad b_{22} = \frac{1}{\alpha} (a_{22} - \varepsilon \ a_{11}),$$

$$b_{12} = \frac{1}{\alpha} (a_{12} + \varepsilon \ a_{21}), \quad b_{21} = \frac{1}{\alpha} (a_{21} + \varepsilon \ a_{12}),$$
where \( \alpha = 1 - \varepsilon^2 \). Hence,

\[
f_{\varepsilon}(A) = \frac{1}{\varepsilon^2} \left[ \det(A) - \varepsilon \left( a_{11}^2 + a_{12}^2 + a_{21}^2 + a_{22}^2 \right) \right].
\]

We claim that \( f_{\varepsilon} \) is not Morrey convex. Indeed \( f_{\varepsilon} \) is not rank-one convex. In fact, setting

\[
I = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}
\]

we have

\[
f_{\varepsilon}(A + t I) = f_{\varepsilon}(A) + \frac{1}{\varepsilon^2} \left( -\varepsilon t^2 + (a_{22} - \varepsilon a_{11}) t \right).
\]

This is clearly not convex with respect to \( t \).

### 5. Euler Lagrange equation

In this section we derive the necessary conditions for an absolute minimizer of the functional

\[
F(u, \Omega) = \text{ess sup}_{x \in \Omega} f(x, u(x), Du(x))
\]

with condition \( u = \psi \) on \( \partial \Omega \). Here \( \psi \) is a given Lipschitz function on \( \partial \Omega \) and an absolute minimizer is defined precisely in:

**Definition 5.1.** A function \( u^* \in W^{1,\infty}(\Omega; \mathbb{R}^m) \) is an absolute minimizer of \( F(u, \Omega) \) if, for any open \( \Omega' \subset \bar{\Omega} \subset \Omega \), \( u^* \) is a minimizer of \( F(u, \Omega') \), where \( u^*|_{\partial \Omega'} = u|_{\partial \Omega'} \). That is, \( u^* \) minimizes \( F \) on every subdomain.

The concept of absolute minimizer localizes the problem and this is necessary since the essential supremum function is a global operator. In integral problems the concept of absolute minimizer is not needed. To see this, suppose that \( u \) is a minimizer of \( \int_{\Omega} f(x, u, Du) \, dx \) with given boundary data \( g \). Let \( \Omega' \subset \bar{\Omega} \subset \Omega \) be any given subdomain and let \( v \) be an appropriate function on \( \Omega' \) with \( v = u \) on \( \partial \Omega' \). Define \( v = u \) on \( \bar{\Omega} \setminus \Omega' \). Then,

\[
\int_{\Omega'} f(x, u, Du) \, dx = \int_{\Omega} f(x, u, Du) \, dx - \int_{\Omega \setminus \Omega'} f(x, u, Du) \, dx \\
\leq \int_{\Omega} f(x, v, Du) \, dx - \int_{\Omega \setminus \Omega'} f(x, v, Du) \, dx \\
= \int_{\Omega'} f(x, v, Du) \, dx.
\]

Hence any minimizer for an integral problem is immediately an absolute minimizer. It is easy to see that the preceding argument fails for \( L^\infty \) problems.
Aronsson [1] derived the Euler equation for $L^\infty$ by using $L^p$ approximations. He noticed that the property of absolutely minimizing is critical in stating that the candidate function satisfies the Euler equation and in all subsequent results depending on the Euler equation. In this section we will not use $L^p$ approximations to derive the Aronsson–Euler equation. Instead we will directly calculate the directional derivative of the functional and then directly use the absolute minimizing property to get the equation we are after. This formal proof, which was carried out in [5] and [8] for the scalar case, distills the critical property of absolute minimizing.

We use the notation

$$f_u(x, u, p) = \begin{pmatrix} \frac{\partial f}{\partial u_1} \\ \vdots \\ \frac{\partial f}{\partial u_m} \end{pmatrix}, \quad f_p(x, u, p) = \begin{pmatrix} \frac{\partial f}{\partial p_{11}} & \cdots & \frac{\partial f}{\partial p_{1n}} \\ \vdots & \ddots & \vdots \\ \frac{\partial f}{\partial p_{m1}} & \cdots & \frac{\partial f}{\partial p_{mn}} \end{pmatrix}.$$ 

**Theorem 5.2.** Let $\Omega \subset \mathbb{R}^n$ be open with compact closure and let $\psi \in C^2(\Omega, \mathbb{R}^m)$ be given. Suppose $f(x, u, p)$ and $f_u, f_p$ are continuous. If $u^* \in C^2(\Omega, \mathbb{R}^m)$ is an absolute minimizer with $u = \psi$ on $\partial \Omega$, then $u^*$ must satisfy the system

$$f_p(x, u^*(x), Du^*(x)) \cdot D_x(f(x, u^*(x), Du^*(x))) = 0, \quad x \in \Omega. \quad (5.1)$$

**Formal proof.** First, observe that we may replace the essential supremum by maximum since we assume $u^*$ is smooth.

Define

$$S = \{ x \in \overline{\Omega} \mid F(u^*, \Omega) = f(x, u^*(x), Du^*(x)) \}.$$ 

If $x_0 \in S$ is an interior point of $\overline{\Omega}$ then we immediately have the condition

$$Df(x, u^*(x), u^*(x))|_{x=x_0} = 0.$$ 

Under our assumption on $f$, $F$ is directionally differentiable for every direction $\gamma \in W^{1,\infty}_0(\Omega; \mathbb{R}^m)$ and, by Danskin’s theorem [11], for example,

$$0 = \left. DF(u^* + \delta \gamma, \Omega) \right|_{\delta=0} = \max \{ f_u(x, u^*(x), Du^*(x)) \gamma(x) + f_p(x, u^*(x), Du^*(x)) D\gamma(x) \mid x \in S \}.$$ 

For any $x_0 \in \Omega \setminus S$, we choose $\varepsilon > 0$ sufficiently small so $\Omega' = B_\varepsilon(x_0) \subset \Omega$. Now we need the absolute minimizing property of $u^*$. We know that $u^*$ minimizes $F(u, B_\varepsilon(x_0))$ and hence for any $\gamma \in W^{1,\infty}_0(B_\varepsilon(x_0); \mathbb{R}^m)$

$$0 = \left. DF(u^* + \delta \gamma, \Omega') \right|_{\delta=0} = \max \{ f_u(x, u^*(x), u^*(x)) \gamma(x) + f_p(x, u^*(x), Du^*(x)) D\gamma(x) \mid x \in S_0 \}, \quad (5.2)$$

where

$$S_0 = \{ x \in \overline{B_\varepsilon(x_0)} \mid F(u^*, B_\varepsilon(x_0)) = f(x, u^*(x), Du^*(x)) \}.$$
Let us choose the direction $\gamma \in W^{1,\infty}_0(B_\varepsilon(x_0); \mathbb{R}^m)$

$$\gamma_i(x) = \frac{\varepsilon^2}{2} - \frac{|x - x_0|^2}{2}, \quad i = 1, 2, \ldots, m.$$ 

Then, from (5.2) we get for some $y \in B_\varepsilon(x_0) \cap S_0$, assuming $y$ is an interior max,

$$0 = f_u(y, u^*(y), Du^*(y))\gamma(y) - f_p(y, u^*(y), Du^*(y)) \cdot (y - x_0).$$

Notice that $y \to x_0$ as $\varepsilon \to 0$ and

$$\lim_{\varepsilon \to 0} \frac{\gamma(y)}{\varepsilon} = 0.$$ 

Therefore dividing by $\varepsilon$ and then sending $\varepsilon \to 0$ we get

$$f_p(x_0, u^*(x_0), Du^*(x_0)) = 0.$$ 

We conclude that $u^*$ must be a solution of the problem

$$\begin{cases}
    f_p(x, u^*(x), Du^*(x)) D_x f(x, u^*(x), Du^*(x)) = 0, & x \in \Omega, \\
    u(x) = g(x), & x \in \partial\Omega. 
\end{cases} \tag{5.3}$$

The equation reduces to $\Delta_\infty u = 0$ in the case $f(x, u, p) = |p|^2$.

Remark 5.3. – In the paper The Euler equation and absolute minimizers of $L^\infty$ functionals we prove the existence of an absolute minimizer for the case $u : \mathbb{R}^n \to \mathbb{R}$, i.e., $m = 1$. We also prove that an absolute minimizer is a viscosity solution of (5.3). The existence and uniqueness of an absolute minimizer in the case $m > 1$ is open.

Remark 5.4. – The special case $f(x, u, Du) = |Du|$ and $u : \mathbb{R}^n \to \mathbb{R}$ was studied extensively in Jensen [12] extending the $C^2$ approach of Aronsson [1–3] to the $W^{1,\infty}$ case. In this case, the necessary conditions for an absolute minimizer results in the Euler equation

$$\Delta_\infty u = Du^t \cdot D^2 u \cdot Du = 0, \quad x \in \Omega, \quad u(x) = \psi(x), \quad x \in \partial\Omega,$$

where $Du^t$ is the transpose of the vector $Du$. This equation is referred to as the Aronsson equation or the $\infty$-Laplace equation and plays the same role in $L^\infty$ as the Laplacian plays in the integral minimum problem for $\int |Du|^2 \, dx$.

REFERENCES

[1] Aronsson G., Minimization problems for the functional $\sup_x F(x, f(x), f'(x))$, Ark. Mat. 6 (1965) 33–53.


