Joint Strength or "Efficiency" Factors of Steel Lap Welded Joints for Use in Water Conveyance

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ABSTRACT

Joint "efficiency" factors are proposed for pressure vessels, piping, and pipelines by ASME standards. For the particular case of non-radiographically-tested lap-welded joints, a low value of joint "efficiency" is proposed. This low value has raised some concerns regarding the use of welded lap joints in geohazard or seismic areas, where significant axial stresses and strains are developed, as a result of ground movement. The paper discusses the joint efficiency concept, mainly in relation with the corresponding failure mode of the pipeline, based on recent experimental observations and numerical simulations. The conservativeness of the ASME "joint efficiency" values for lap-welded joints is demonstrated. Furthermore, based on experimental evidence, it is shown that lap welded joints can sustain significant deformation, without loss of pressure containment. The conclusions from this paper support the argument that lap welded joints constitute a simple, efficient, and economical solution for pipeline joints in seismic areas.

1 INTRODUCTION

The concept of joint efficiency was introduced by ASME code in the 1930s (American Standards Association, 1935), and later adopted by API standards dealing with pressure containment structures that typically operate at high pressures and/or temperatures. Joint efficiency is expressed by a numerical value or, equivalently a percentage, referred to as "joint efficiency factor", defined as the ratio of the "strength" of a joint (riveted, welded, or brazed) over the "strength" of the base material. This factor is also a way to introduce "safety" factors in design of welded shell structures for pressure containment. In the ASME or API codes, joint efficiency values in welded connections under tension depend on: (a) the type of welded joint (e.g. full-penetration butt-weld, single or double fillet lap weld etc.), (b) the extent of non-destructive examination or testing required for the weld under consideration and (c) the location or orientation of the joint. For a more extensive historical development of the joint efficiency factor in ASME codes and standards the reader is referred to the recent publication by Rosenfield (2012) .

The AWWA M11 Design Manual for steel welded pipelines for water transmission does not adopt the "joint efficiency" concept. On the other hand, Table UW-12 from ASME B&PV Code part VIII, Division 1, specifies joint efficiency values for welded lap joints equal to only 55% and 45% for non-radiographically-tested double-welded and single-welded joints respectively (see also Table 1 of the present paper). Because of those low values, some engineers argue that those joints may not be suitable for use in geohazard (seismic) areas. When subjected to ground-induced actions, the pipeline exhibits significant longitudinal (axial) stresses and strains, which affect directly the pipeline circumferential welds. By consequence, according to that argument, welded lap joints are perceived as very weak and vulnerable locations of steel pipelines, with significantly reduced strength.

The present paper is motivated by the use of welded steel pipelines in geohazard (seismic) areas, where severe longitudinal stress and strain develops, in addition to internal pressure. The paper revisits the concept of welded lap joint efficiency, based on past experiments, as well a series of recent experimental and numerical studies on welded lap joints, subjected to internal pressure and structural loading. Those studies have demonstrated that both strength and deformation capacity of welded joints is significantly higher, comparable with the strength of the plain pipe. Previous analytical attempts to quantify joint efficiency in lap welded joints are revisited and evaluated. Furthermore, the inter-relation between "joint efficiency" and "joint strength" is extensively discussed, and the main differences are identified. Finally, the paper is aimed at re-examining the concept of "joint efficiency" in welded lap joints. It is shown that the joint efficiency values in ASME VIII – Div. 1 are quite conservative and – in several cases – irrelevant to pipeline seismic design. The structural behavior and strength of welded lap joints is discussed extensively for severe structural loading (bending, axial) in the presence of pressure, a loading pattern quite frequent in seismic areas. The conclusions of the paper can be used for increasing confidence in the use of welded lap pipeline joints in seismic areas, towards more rational and economical steel pipeline design.

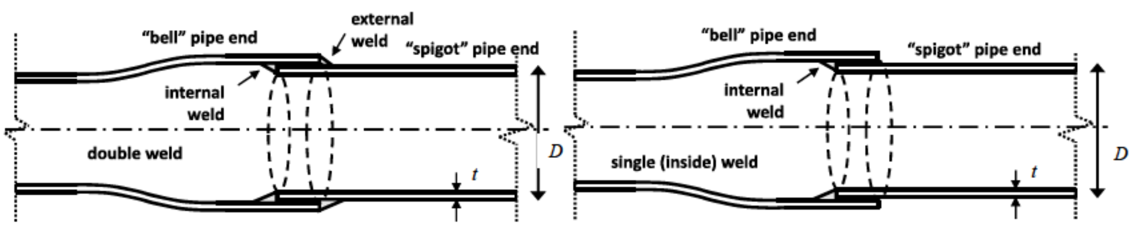

Figure 1. Schematically configuration of two types of lap pipe joint (double welded, and single welded).

Table 1: Table UW-12 (part) from ASME VIII – Division 1

Type No.	Joint Description	(a) Full RT(*)	(b) Spot RT	(a) No RT
1	Butt joints as attained by double-welding or by other means which will obtain the same quality of deposited weld metal on the inside and outside weld surfaces to agree with the requirements of UW-35. Welds using metal backing strips which remain in place are excluded.	1.0	0.85	0.70
4	Double full-fillet lap-joint	N/A	N/A	0.55
6	Single full-fillet lap-joint without plug welds	N/A	N/A	0.45

(*)RT = Radiographically Tested

2 PROBLEM STATEMENT

The main current source for joint "efficiency" factors related to lap welded joints in pressurized cylinders is Table UW-12 from the ASME B&PV Code part VIII, Division 1, summarized in Table 1 of the present paper for the cases of interest. The Table specifies a joint efficiency value for welded lap joints equal to 55% and 45% for non-radiographically-tested double and single welded joints. These low values of welded lap joint efficiency has caused quite some controversy, to be discussed extensively in the present paper.

In contrast to the ASME B&PV code, wall thickness calculation in Chapter 4 of AWWA M11 (Eq 4-1) employs the well-known hoop stress equation in thin-walled cylinder, written below in a more convenient form in terms of the hoop stress σ_h:

$$\sigma_h \leq \sigma_{allow} \tag{1}$$

where

$$\sigma_h = \frac{pD}{2t} \tag{2}$$

In the above expressions (1) and (2), D and t are the diameter and thickness of the steel pipe and σ_{allow} is the allowable stress of the steel material, equal to 50% of specified minimum yield stress σ_Y for the operating or working pressure design condition, whereas σ_{allow} for transient or field test design conditions is 75% of σ_Y. Having determined pipe wall thickness from (1) and (2), the structural adequacy of welded-lap joints is performed according to AWWA M11 provisions (Chapter 6), considering the longitudinal stress σ_L. For pressure load only, the longitudinal stress verification can be written as follows:

$$\sigma_L \leq 0.7\sigma_{allow} \tag{3}$$

The value of σ_L depends on the end conditions; for "thrust end" conditions, sometimes referred to as "capped end" conditions, σ_L is equal to $0.5\sigma_h$. Under plane-strain conditions, also referred to as "Poisson" conditions, σ_L is equal to $0.3\sigma_h$. Furthermore, the weld allowable stress of the weld is equal to $0.7\sigma_{allow}$, so that the size of weld throat is taken into account in the calculation[1]. Therefore, equation **(3)** can be written in an equivalent form in terms of hoop stress σ_h as follows:

$$\sigma_h \leq \frac{0.7}{\alpha}\sigma_{allow} \tag{4}$$

where α is equal to 0.5 or 0.3 depending on the end conditions. Using a value of 0.5 for α, one obtains from inequality (4)

$$\sigma_h \leq 1.4\sigma_{allow} \tag{5}$$

whereas, when α is equal to 0.3, inequality (4) becomes

$$\sigma_h \leq 2.33\sigma_{allow} \tag{6}$$

Comparing (5) and (6) with (1), it is readily concluded that longitudinal stress may not govern the pressure design, also noted in AWWA M11. In the case of combined pressure and thermal stress design, the longitudinal stress σ_L is equal to $\alpha\sigma_h + \sigma_T$, but M11 proposes a higher allowable stress σ'_{allow}, so that:

$$\alpha\sigma_h + \sigma_T \leq \sigma'_{allow} \tag{7}$$

The above design procedure is well documented in AWWA M11 and does not employ any efficiency factor for wall thickness determination and for welded lap joint design. On the other

[1]This is a significant difference with the ASME code, where calculations on fillet welds are based on the weld leg, and not at the weld throat.

hand, some engineers have been expressed concerns on the adequacy of lap welded joints to sustain longitudinal stress. This argument has been expressed as follows (see also Call & Sundberg, 2007): for internal pressure only, considering an allowable stress that includes the ASME joint efficiency factor (denoted here as f_E), the longitudinal stress design equation becomes:

$$\alpha\sigma_h \le f_E\,\sigma_{allow} \tag{8}$$

Using value of α equal to 0.5 and f_E equal to 0.45 (single-welded lap joint) in **(8)** one obtains:

$$\sigma_h \le 0.90\,\sigma_{allow} \tag{9}$$

Comparing (9) with (1), it may be concluded that longitudinal stress governs pressure design, and a 10% thicker pipe is required for the case of single-welded lap joints. In addition, if longitudinal stress from seismic action is added to the left-hand-side of inequality (8) the situation may become more critical.

The present paper offers an extensive critical discussion of the above argument, in an attempt to dissolve a "myth" that has developed on the vulnerability of lap welded joints in seismic areas, expressed mainly by the argument described above. The paper focuses on two main issues: (a) the conservativeness of the joint efficiency factor, as proposed by ASME VIII – Div. 1; (b) the relevance (or irrelevance) of the factor joint efficiency concept the seismic design philosophy of welded steel pipelines.

3 INTERNAL PRESSURE DESIGN ACCORDING TO ASME STANDARDS

ASME B31 standards refer to the mechanical (structural) design of pipelines. Among all the B31 standards, ASME B31.4 refers to transportation of liquids, and is the closest to steel water pipelines and will be used in our discussion. In B31.4, pressure design is expressed by the following equation (section 403.2), written here in a convenient form:

$$\sigma_h \le f_E\,\hat{\sigma}_{allow} \tag{10}$$

The above inequality has quite some similarities with **(1)**, but a joint efficiency factor f_E is included. Values of the joint efficiency factor are taken from Table 403.2.1-1, but refer to line pipe (factory) welds of the pipe barrel. Lap welded joints are not considered in ASME B31.4 specification. Furthermore, values of allowable stress $\hat{\sigma}_{allow}$ is the product of the specified minimum yield stress σ_Y with a design factor, not greater than 0.72.

ASME B&PV section VIII – Division 1 is a widely used code for pressure vessels, and makes use of the joint efficiency concept. Section UG-27 states the following expressions for pressure design, referring to both hoop and longitudinal (axial) stress, written here in a more convenient form:

$$\sigma_h \le f_{EL}\,\hat{\sigma}_{allow} \tag{11}$$

and

$$\sigma_h \le 2 f_{EC}\,\hat{\sigma}_{allow} \tag{12}$$

The above expressions are simplified versions of the expressions in ASME VIII, considering the large value of the diameter-to-thickness ratio in steel water pipelines. Because of the limited length of a pressure vessel, the longitudinal stress σ_L is always half of the hoop stress σ_h ($\sigma_L = 0.5\sigma_h$). Furthermore, Table UW-12 provides joint efficiencies values for the longitudinal weld f_{EL} and for the circumferential weld f_{EC}. This Table includes lap welded joints, which may sometimes be used for the pressure vessel caps. It should be noted though that ASME VIII is a "safety" code for pressure vessels. It does not refer to pipelines, and should be cautiously used, especially for the case of pipeline seismic design. This issue will be addresses in the following sessions.

4 PREVIOUS CALCULATIONS OF "JOINT EFFICIENCY"

Several attempts have been reported to define analytically an efficiency factor for lap welded joints. Among other attempts, it is worth mentioning Moser (2001), who performed an elastic analysis on a two-dimensional longitudinal pipe strip containing the lap joint, subjected to axial load. Moser considered the extra bending stress in the bell due to the eccentricity of the axial load with respect to the bell mid-surface and resulted in a total stress (i.e. the sum of axial and bending stress) equal to 7 times the nominal axial stress. Therefore, he concluded – indirectly – that this high stress is responsible for the failure of lap joints in a case study reported by Moncarz *et al*. (1987). Quite often, Moser's calculation is used for justifying the low f_E value for lap joints in ASME VIII. However, it is the authors' opinion that relating joint efficiency with this type of analysis may not be appropriate; this is an elastic analysis of a two-dimensional strip, which is far from reality: an elastic-plastic analysis of the three-dimensional geometry is necessary. The reader is also referred to the paper by Watkins *et al*. (2006) for a more extensive discussion on this matter.

Another, somewhat more elaborate analytical approach for determining joint efficiency has been reported by Brockenbrough (1990), and later by Van Greusen (2006). This is an elastic-plastic approach, which is also based on a two-dimensional analysis of a longitudinal pipe strip, containing the lap joint. In this analysis, joint efficiency is defined as the axial load F_a required for the entire bell section to become plastic over the plastic load F_P of the pipe cylinder section ($f_E = F_a/F_P$). Note that $F_P = \sigma_Y tb$, where b is the width of the strip considered in the analysis. The analysis assumes an elastic-perfectly plastic material and considers the extra bending moment due to bell eccentricity, and results in "joint efficiencies" that depend on the gap between the bell and spigot. For zero gap, the maximum value of the F_a/F_P is obtained, equal to 0.41, which is not far from the ASME value for single-welded lap joint in Table 1. However, this analysis does not consider the three-dimensional configuration of the pipe joint and ignores the change of geometry upon development of plastic deformation at the joint section. Therefore, it is the authors' opinion that this results to conservative approach, and to unreasonably low values of joint efficiency.

5 BEHAVIOR OF LAP WELDED JOINTS AGAINST SEVERE STRUCTURAL LOADING

In the present section, we describe structural behavior of welded lap joints, based on available data from physical experiments and rigorous numerical simulations, reported elsewhere, supported by engineering judgement. It is our purpose to describe the real behavior under the main loading patterns, namely axial tension, axial compression and bending, in terms of the corresponding failure mode, in an attempt to show whether this is relevant or not to the joint efficiency concept.

A first important note is necessary at this point. When a pipeline is subjected to severe structural loading (bending and/or axial) stemming from seismic (or geohazard) action, its response is quite different than pressure loading. In this case, the response is associated with the development of severe stress and strain in the longitudinal direction of the pipeline, perpendicular to the fillet lap weld[2]. Furthermore, this stress and strain will be well beyond the elastic limit of pipeline material, associated with severe plastic deformation at the vicinity of the joint. Therefore, the classical stress approach may not be adequate, and a strain-based approach is necessary for efficient pipeline design. Therefore, one has to ensure that the longitudinal strain can be sustained by the welded joint, in order to prevent failure of the weld (fracture) and loss of pipeline containment.

A second issue refers to the "strength" of the joint under consideration. Quite often, joint efficiency is directly related to "joint strength". Although there exist some similarities in those two concepts, however, this is not always true. The main issue in our present discussion is that "joint efficiency" should be related to the failure mode of the joint and not to its "strength". More specifically, the failure mode is the "limit state" at which the pipeline becomes not capable of fulfilling its transmission function, because of containment loss. Clearly, this limit state is associated with fracture of the joint. On the other hand, the "strength" of the joint, i.e. the maximum load that the joint can sustain may not necessarily correspond to this limit state. More specifically, the occurrence of a local buckle at the vicinity of a pipeline joint, due to excessive compression, corresponds to the maximum load that the pipe can sustain. However, recent experiments (Keil *et al*., 2018) on welded lap joints have indicated that buckled pipe joints are capable of deforming significantly beyond that stage, without loss of containment.

In the following paragraphs, the mechanical response of welded lap joints under severe external loading is discussed for the three main types of loading (bending, axial compression and axial tension). Reference to previous relevant publications is made.

5.1 Axial tension

Axial tension is the most direct loading condition for the circumferential joint. It does not imply any buckling phenomena, and therefore, in this case, joint strength can be directly related to joint efficiency. Excessive axial tension results in pipeline rupture, mainly because of weld fracture. It is a local-type failure mode, which is strain-driven rather than stress-driven, in the sense that failure occurs at strain well into the plastic range. The value of strain at which this failure occurs depends on the quality of the weld and the presence of possible defects. It is the authors' opinion that, unless a serious defect is present, which is unlikely to occur in a real pipeline application, where AWWA C206 welding provisions are met, the strain at which failure occurs is well into the inelastic range of steel material, whereas the corresponding stress would be somewhat higher than the yield stress, because of material strain hardening.

There exist very limited tests of lap welded pipe joints subjected to tension. To the authors' knowledge, the only tests available are the two (2) tests reported by Mason *et al*. (2010a). The tests indicate that the two lap joints were capable of sustaining significant tension load and deformation, and fracture occurred away from the joint, at the pipe cylinder. However, those tests refer to small-diameter 12-inch non-pressurized pipes, with diameter-to-thickness D/t ratio equal to 50, which is outside the range of interest.

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[2]It is reminded to the reader than, in pressure design, hoop stress controls.

Based on the above discussion, it is necessary to perform tests on larger diameter pressurized pipes, containing lap welded joints, so that both strength and deformation capacity of lap welded joints are determined. Nevertheless, it is the authors' opinion that the values of 0.55 and 0.45 for double-welded or single-welded lap joints stated in ASME VIII are unreasonably low and penalize unnecessarily the design of those joints.

5.2 Axial compression

This type of loading is associated with the development of uniform compressive stress/strain, which results in local buckling of the pipe at the joint area, a shell-type of buckling. Under zero or low levels of pressure, the buckling pattern is non-axisymmetric, reminiscent of diamond-shape buckling, whereas for higher level of pressure, the buckling shape is characterized by an axisymmetric bulge at the lap joint bell.

There exist limited experimental data on the axial response of welded lap joints. Full-scale compression tests on 77.625-inch-diameter pipes have been reported by Smith (2006). The specimen contained a serious of joints (butt, single lap, single lap with large gap, modified bell, double weld gap and reinforced bell), and it was compressed in the absence of internal pressure until local buckling occurred at the single lap weld with large gap, in the form of a "diamond-shape" pattern. Subsequently, it was pressurized to yield pressure level, and no leakage has been detected.

The compression tests by Tutuncu (2001) and Mason (2006), also summarized by Mason *et al*. (2010b) are the only source of information available. Three of those tests refer to specimens with diameter size 32 in and 36 in, and diameter-to-thickness ratio ranging between 144 and 255. The strength of the specimens, associated with the buckling strength of the lap joint was found to range between 43% and 66% of the axial compressive strength of the plain pipe (which was computed numerically through finite element analysis). Due to the eccentricity of the bell, buckling has occurred at that area. Upon buckling, the specimens continue to deform in compression, with decreasing axial force, while the deformation localizes at the joint region. However, the tested specimens were not internally pressurized, and no information has been provided regarding possible weld fracture at the post-weld regime.

In summary, the above test results indicate that:

(a) The joint strength under compressive loading ranges between 43%-66% of the compressive (buckling) strength of the pipe cylinder.

(b) Joint failure (rupture) may occur far from this local buckling stage, and depends on the local strains at the buckled area.

Therefore, in the case of axial compression, joint strength may not be related to joint efficiency. Joint strength refers to the buckling load, whereas "joint efficiency" mainly depends on the joint capacity to sustain the local strains developed at the buckled area. To determine appropriate deformation limits for axially compressed pipelines with lap welded joints, a series of dedicated tests on pressurized lap welded joint specimens is required.

5.3 Bending loading

Longitudinal bending causes both tension and compression at the "extrados" and "intrados" of the bent pipe respectively. Therefore, the issues discussed above for pure axial compression and tension are both applicable in the bending case. Structural instability occurs at the compression zone in the form of a local buckle, whereas large tensile strains developed at the tension side, which may lead to weld fracture and immediate loss of containment.

Experiments on lap welded steel pipe joints have been recently reported by Keil *et al*. (2018), supported by numerical simulations (Chatzopoulou *et al*., 2018). The tests refer to pipes with diameter-to-thickness ratio equal to 190 and 103, pressurized to 40% of the yield pressure. The magnitude of tensile strains may be significantly increased after buckling of the compressive zone occurs, due to localization of deformation. In the absence of internal pressure, or under low pressure levels, buckling has a non-axisymmetric shape, reminiscent of the "diamond-shape" buckle observed under axial compression, whereas beyond a certain pressure level, the buckling shape is characterized by an outward bulge at the compression zone.

The bending "strength" of a lap welded joint can be defined as the ratio of the maximum bending moment that the joint can sustain over the maximum bending moment sustained by the pipe cylinder. This ratio for the case of pipe specimens with D/t ratio equal to 192, has been measured equal to 81%, and this has been verified by numerical analyses. On the other hand, it is important to notice that the maximum bending moment occurs at relatively low values of bending deformation and that, upon buckling, the pipe specimens were capable of sustaining significant deformation without loss of pressure containment, as shown in Figure 2. Pressurized lap-welded pipe joint specimens, subjected to bending; (a) post-buckling configuration during testing; (b) shape of buckle. Furthermore, during the tests, high values of local strain have been measured that exceeded 3%, indicating a very good performance of the welded joint. It should also be noticed that the corresponding strain gages have a certain distance from the weld toe, for practical instrumentation reasons, so that local strains at the immediate vicinity of the weld toe are expected to be significantly higher.

Summarizing the conclusions from the above experiments, the results have indicated that

(a) The joint strength under bending loading is approximately 81% of the bending strength of the pipe cylinder, associated with local buckling at the compression zone.
(b) Joint failure (rupture) may occur far beyond from this buckling stage, and depends on the local strains developed at the buckled area.

Currently, deformation limits for steel lap-welded pipelines are being developed, for the purpose of being included in the new ASCE MoP for seismic design of buried pipelines. The results from the above experiments and the corresponding numerical simulations can contribute to the development of reliable limits for welded lap joints.

6 SUMMARY AND CONCLUSIONS

The present paper addresses the issue of joint "efficiency" and "strength" of lap welded steel pipe joints in a simple manner, in conjunction with the seismic design and behavior of steel water pipelines. Following a review of some basic concepts, and a critical discussion of relevant provisions in AWWA M11 and ASME codes, the behavior of lap joints under severe loading conditions is presented in detail, with reference to observations from physical tests and numerical simulations reported elsewhere. In addition, a critical evaluation of joint efficiency calculations has been presented, demonstrating the inadequacy of those approaches in providing a reliable value of joint efficiency. Based on the above extensive discussion, the following important issues should be underlined:

- The joint efficiency concept is not employed by AWWA M11 design manual.
- The low values of joint efficiency in ASME VIII – Div.1 are not justified. Furthermore, they refer to pressure vessel design, and may not be directly applicable to pipeline design.
- AWWA and ASME standards use different design methods for different applications. Mixing and matching these methods together is neither recommended nor proper design.

This may create a final design that is unpredictable, and unreliable, leading perhaps to either overtly conservative or possibly unsafe design.

- For the case of seismic design, it is necessary to re-define "joint efficiency" of lap welded joints, and relate it to the ultimate limit state of the pipe (failure mode), which is the "loss of pressure containment".
- "Joint strength" may not necessarily be related to "joint efficiency"; recent test results in the case of compressive loading (axial compression or bending) the joint is capable of sustaining significant post-buckling deformation without loss of containment.

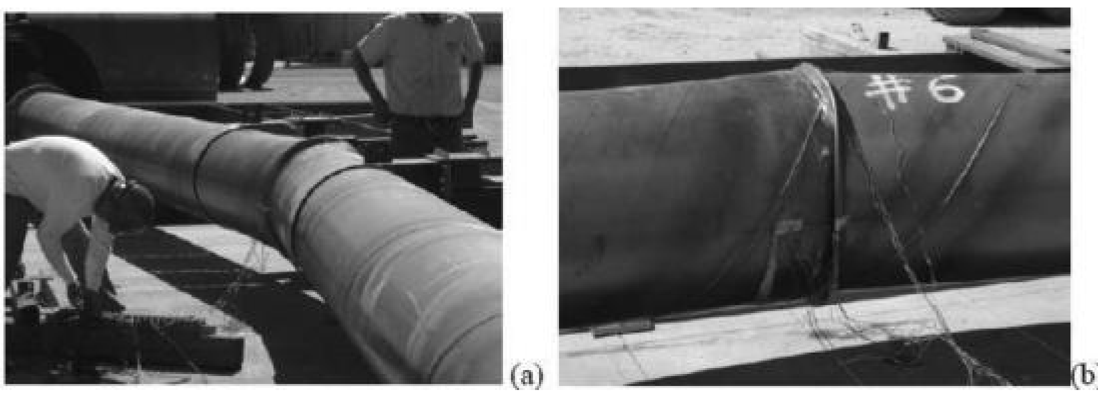

Figure 2. Pressurized lap-welded pipe joint specimens, subjected to bending; (a) post-buckling configuration during testing; (b) shape of buckle.

Finally, it is important to note that an experimental program is underway, for the purpose of determining the mechanical behavior, resistance and deformation capacity of lap-welded steel pipe joints subjected to extreme structural loads in the presence of internal pressure. Completion of those tests, a more

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