Commentary on Highly Restrained Welded Connections

AMERICAN INSTITUTE OF STEEL CONSTRUCTION

FOREWORD

The American Institute of Steel Construction, recognizing the need for dissemination of information to designers and fabricator-erectors on potential problems encountered in highly restrained welded connections, created a Task Force with the assigned responsibility of reviewing published relevant technical literature to develop a discussion of the factors and mechanisms that would be useful to the design profession and construction industry. The report of this Task Force of the AISC Committee on Fabricating Operations and Quality Standards resulted in this document, which is a "State of the Art" presentation reflecting information presently available.

With regard to the points raised in this commentary concerning highly restrained welded connections, it is emphasized that for the great majority of welded connections the conditions which provide the potential for lamellar tearing or other distress do not exist. It is only in a limited number of connections in welded structures that critical requisite conditions may precipitate a lamellar tear. The purpose of this paper is to present information which will be an aid in minimizing the occurrence of such conditions.

Numerous authoritative research reports and much information on lamellar tearing have been reviewed and presented concisely in this commentary; however, information on this subject is incomplete and research work is continuing throughout the world; therefore, no attempt is made to make specific recommendations at this time. It should be noted that while this paper deals specifically with the lamellar tearing phenomenon, it is not intended to be a complete guide covering all potential difficulties (such as brittle fracture, underbead cracking, fatigue) that may result from improper joint designs. Even though modern ultrasonic testing may tend to spotlight lamellar tearing, these other factors, which often may be more serious, must be considered by the designer. This commentary is not intended in any sense to be a substitute for individual expertise in a particular application.

While every precaution has been taken to insure the information is as accurate as possible, the American Institute of Steel Construction disclaims responsibility for the authenticity of the information herein and does not guarantee that in specific applications any of the material contained in this paper will prevent lamellar tears.

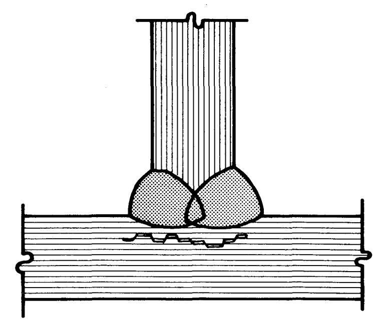


Fig. 1. Joint showing typical lamellar tear resulting from shrinkage of large welds in thick material under high restraint

INTRODUCTION

With the rapid increase in welded applications and the use of heavier members, more frequent instances of high restraint are being encountered in typical structural designs. Occurrence of lamellar tearing in some highly restrained joints in actual structures has been reported.

Lamellar tearing is the separation in the parent or base material caused by "thru-thickness" strains induced by weld metal shrinkage (see Fig. 1).* Under conditions of high restraint, localized strains due to weld metal shrinkage can be many times higher than yield point strains, whereas stresses due to design loads are only a fraction of yield point; thus, the strains due to applied loads are not of primary concern in causing lamellar tearing. No cases are known of lamellar tears being initiated or propagated by design loads.

* *The term "lamellar" should not be confused with the term "lamination". See Glossary.*

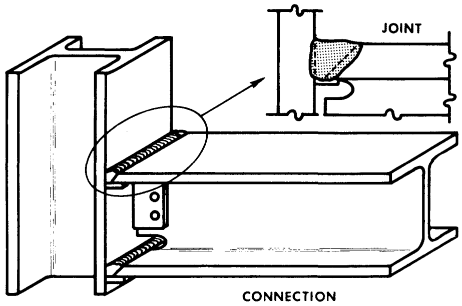


Fig. 2. Typical moment connection with full penetration welded flange joint

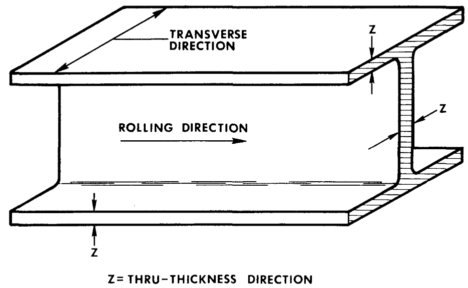


Fig. 3. Terminology related to rolling direction

It is important to recognize that joint restraint as discussed in this paper is not the connection restraint that designers count upon in the analysis of rigid frame structures (Fig. 2). Properly designed restrained connections which transfer frame bending moments from one structural member to another do not generally induce localized strains responsible for lamellar tearing. The restraint that is of concern is *internal* restraint (within a connection made up of several joints) which inhibits the small *total*—but large *unit*—localized strains resulting from weld shrinkage. These strains are inevitable, because the solidified weld metal contracts while it cools. High internal joint restraint can occur in connections which are not counted on to provide frame continuity, as well as in rigid frame connections. In either case the connections can be designed in a manner which will reduce internal localized strains.

The purpose of this paper is to present information on the subject of lamellar tearing and to correct misconceptions to the end that the occurrence of this phenomenon will be minimized.

DEFINITION OF THE PHENOMENON

Design codes and specifications have tended to focus attention on the relationship between calculated and allowable stresses. The result has been that there is often a lack of recognition that under certain conditions localized *strain* is significantly more important than *stress*. In fact, stress may be quite unimportant. It is recognized and accepted that fasteners, welds, and local areas of the connected material must yield even before design loads are applied. The calculated *unit* stresses, which are used as a convenient means of proportioning connections, may bear no relationship to actual local stresses. The lack of general recognition of the importance of unit strains, rather than stresses, makes it appropriate to present a discussion of the mechanisms involved.

Up to the elastic limit, stress is proportional to strain. Beyond the elastic limit, as strain is increased, the steel elongates or compresses without significant increase in stress (deforms plastically) to the point where strain hardening occurs and further strains are accommodated with increasing stress up to the rupture load, which occurs at a level many times (in the range of 100 times) the strain at the elastic limit. The property of being able to deform plastically is *ductility*.

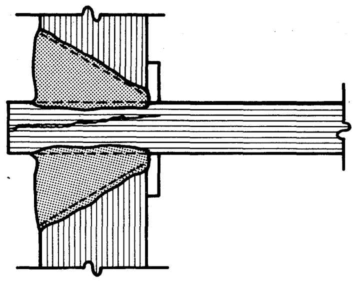
Steel loaded parallel or transverse to the rolling direction exhibits this ductility to a greater degree than steel loaded in the thru-thickness direction (see Fig. 3).

In the elastic range, the thru-thickness strength of steel is relatively close to the strength in the longitudinal or transverse direction (i.e., the elastic limit is only slightly below that as determined by use of standard test coupons and test procedures). On the other hand, steel loaded in the thru-thickness direction may have limited capacity to be strained in excess of the elastic limit strains.

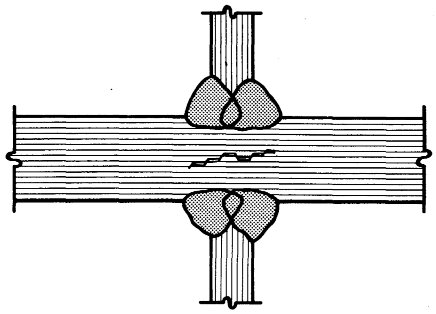
Steel may be counted upon to deform locally parallel and transverse to the rolling direction and, if deformed enough, to bring about a redistribution of the forces in such a way that the localized highly stressed areas refuse to accept additional load and call upon surrounding material to share in the load transfer. In the thru-thickness direction, strains in excess of the yield point may cause decohesion and lead to a lamellar tear.

A lamellar tear occurs only in the parent metal and, while it may originate close to the toe or root of the weld, often the tear may originate well outside the heat affected zone and may not propagate to the surface. The cross section of a lamellar tear is steplike, with longitudinal terraces that are markedly longer than the transverse portions. (See Figs. 4 and 5.) The fracture has a fibrous appearance (Fig. 6), and this characteristic, along with the terraced profile and location within the base material away from the weld fusion line, is the best way of distinguishing the lamellar tear from cracks in the heat-affected zone caused by hydrogen.

The tearing occurs principally in tee and corner type joints where the degree of restraint which exists is



(a)



(b)

Fig 4. Contraction of large weld joints can strain the interposed plate beyond the limit of thru-thickness ductility, producing a lamellar tear

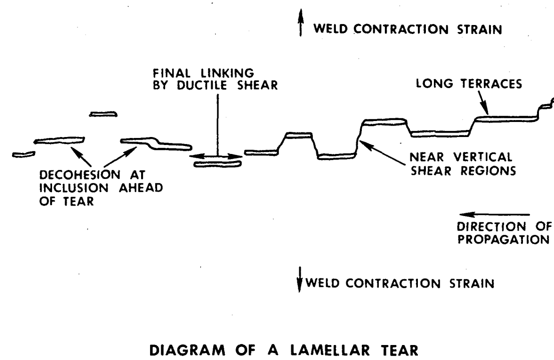


Fig. 7. Diagram of a partially developed lamellar tear

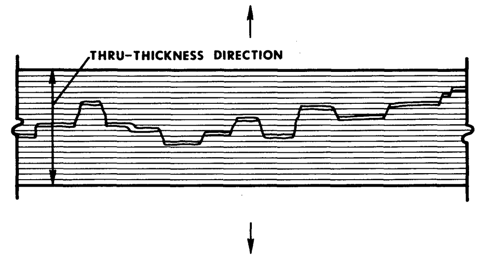


Fig. 8. Cross section of parent material showing complete development of the incomplete tear shown in Fig. 7

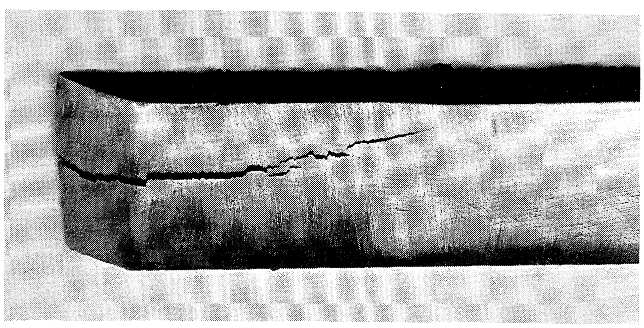


Fig. 5. Typical lamellar tear due to large thru-thickness strains. Note horizontal terraces with short vertical shear planes.

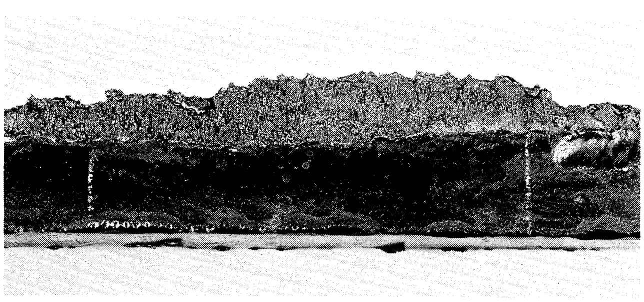


Fig. 6. Characteristic fibrous surface of lamellar tear

such that weld shrinkage strains imposed on the parent metal in the thru-thickness direction cannot be accommodated because of limited ductility. During the progress of welding, after a sufficient number of passes have been deposited, the weld shrinkage strains increase in magnitude as the weld cools, to a degree where decohesion occurs at the interface between microscopic non-metallic inclusions and surrounding matrix. As more weld metal is deposited, additional microscopic tears form. Since the non-metallic inclusions and strains are dispersed through the steel in an irregular manner, the tear takes the most susceptible path (Fig. 7). Subsequent completion of the weld followed by cooling to ambient temperature increases strains so that terraces resulting from decohesion link together by shearing failure to form the completed lamellar tear (Fig. 8).

The important consideration which must be kept in mind is to minimize the concentration of strains in localized areas. For example, the arbitrary requirement for full penetration welds where they are not actually required is a serious error which increases strains in localized areas and can contribute to the incidence of lamellar tears in welded connections which load the material in the thru-thickness direction (especially when large multiple-pass groove welds are involved).

Fig. 9. *Unetched photomicrograph of microscopic inclusions as cast in steel ingot (magnification 100×)*

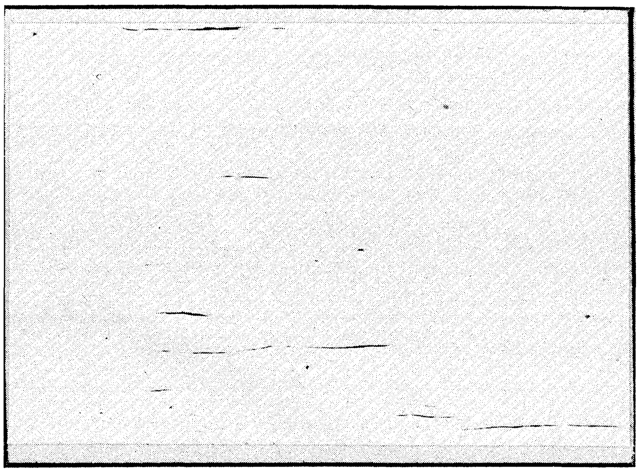


Fig. 10. *Unetched photomicrograph of microscopic inclusions elongated during rolling (magnification 100×)*

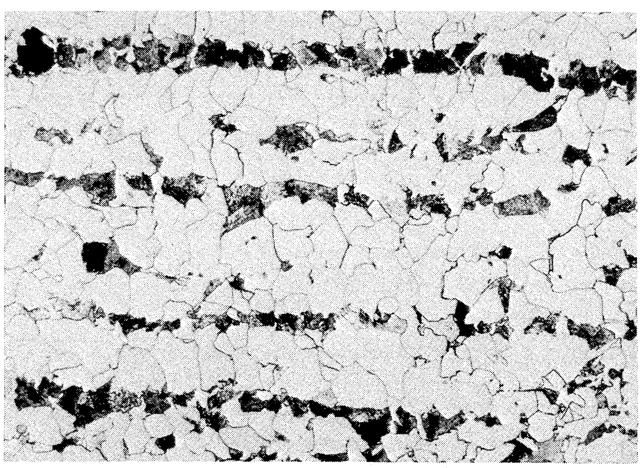


Fig. 11. *Etched photomicrograph of banded microstructure in hot rolled steel (magnification 157×)*

FACTORS CONTRIBUTING TO LAMELLAR TEARING

Connected Material Properties—Joints which stress the steel in the thru-thickness direction do not necessarily cause difficulty. However, in a highly restrained design, if the weld shrinkage strains tend to pull the steel apart in the thru-thickness direction, the joint will exhibit a greater tearing tendency than when the shrinkage forces are oriented in the plane of the member. The reason for this is that the hot rolling process used to shape structural steels produces the greatest strength and ductility in the longitudinal and transverse directions, which are of most importance to the structure, with usually lesser ductility in the thru-thickness direction. Elongation and area reduction values may well be significantly lower in the thru-thickness direction than in the rolling direction. Discontinuities or laminations parallel to the direction of stress do not have a detrimental effect upon the strength of the members. This dependence of steel properties upon orientation with respect to rolling direction is of small consequence in the design of riveted, bolted, or low-restraint welded connections. It can become a critically important consideration in the design and fabrication of structures containing massive members with highly restrained welded joints.

Microscopic non-metallic inclusions can cause reduction in thru-thickness ductility, although inclusion counts have not been established as a direct measure of susceptibility to lamellar tearing in highly restrained welded connections. These inclusions consist primarily of residues from additions which are made to liquid steel to improve the product by reducing the oxygen content and refining the grain structure. The inclusions as cast (Fig. 9) consist primarily of sulphides, oxides, and silicates which are progressively elongated longitudinally and spread laterally parallel to the rolled surface to varying degrees, depending on the method of rolling, as the steel is rolled into a plate or shape (Fig. 10).

Hot rolled structural steel may, depending upon the microstructure of a particular rolled section, exhibit a structure of layered pearlite patches in ferrite. This is often called a banded structure (Fig. 11). No relationship has been established through laboratory tests between banding and lamellar tearing, and such steel fully meets both mechanical and chemical requirements of the ASTM specification for the particular steel grade. Research has shown that most lamellar tears have a short stepped or short terraced type of surface, indicating that banding is not the dominant influence; if it were, the tears would continue along the bands for a greater length.

The steel industry is continually striving to improve techniques for the production of steel and to reduce the incidence of non-metallic inclusions. However, there are both economic and technical limitations involved in achieving metallurgical improvements in resistance to lamellar tearing. Although continual progress is being made, it is unlikely that there will soon be a breakthrough that would eliminate non-metallic inclusions and change the anisotropic character of economical structural steels.

The technical literature states that it is not possible to determine the susceptibility of steel to lamellar tearing by ultrasonic or other non-destructive methods. In the case of existing structural steels, even when material free of detectable discontinuities is selected by use of a screening process, the chance of lamellar tearing in poorly designed connections is not significantly reduced. Therefore, specifications calling for premium material can cause a substantial increase in its cost in the structure without corresponding improvement in strength or reliability of the total structure.

Weld Metal Properties—The requirements for electrodes, wires, and fluxes for use with "matching" base metals are well defined in the American Welding Society (AWS) *Structural Welding Code, D1.1-72* and in the AISC *Specification for the Design, Fabrication and Erection of Structural Steel for Buildings, 1969.* In general, the "matching" of weld metal to base metal is made on the basis of tensile strengths. When weld metal is selected that will match closely the tensile strengths of structural grade steels, the weld yield points are generally significantly higher than those of the base materials. For example, the specified minimum yield point of weld metal from E70XX electrodes is 57 ksi as compared with 36 ksi for A36 material parallel to the direction of rolling. The typical result is that yield point strains occur in the connected material at a level of stress where the stress in the weld metal is still well below its yield point. Thus, the total strain is forced to take place in the connected material. Over-matching of electrodes to connected material compounds the problem. Lower yield strength weld metal aids in redistribution of strains; however, at the present time, commercially available electrodes produce deposited weld metal having minimum yield points of about 50 ksi or higher.

Strains Induced by Restraint to Weld Contraction—As a weld cools to ambient temperature, its contraction induces strains which, if forced by connection geometry to take place in localized areas, may be in excess of the strains normally occurring at the yield point of the connected metal. If the pieces joined are relatively thin or free to move, the strain can be reduced by distortion. If the members are restrained from moving by the out-of-plane bending stiffness of thick material, rigid abutment between adjacent elements of the connection, and/or previously installed stiffeners, the localized shrinkage strains may become large and may induce lamellar tearing.

Because shrinkage and residual stresses tend to increase with the volume of weld metal deposited, the probability of lamellar tearing also increases. In large volume multi-pass groove welds, the high restraint created by initial weld passes apparently forces the strains from subsequent weld passes to concentrate in a highly localized area. This does not appear to be true in the case of electroslag welds which have a large volume but are deposited in a single pass, minimizing the prying effect from differential cooling strains. However, electroslag welded connections are feasible only in certain situations.

Examples of Highly Restrained Connections—Following are some typical examples of connections which provide high restraint against the contraction of solidified weld metal and induce strains in the thru-thickness direction. These and similar connections require special consideration in minimizing high internal localized strains.

1. In a beam-to-column connection, when both the web and flanges are welded directly to a thick column flange (Fig. 12) or a stiffened thin column flange (Fig. 13), high restraint will oppose the contraction of the last welds to be made and force strains to concentrate in the thru-thickness direction in the column flange.

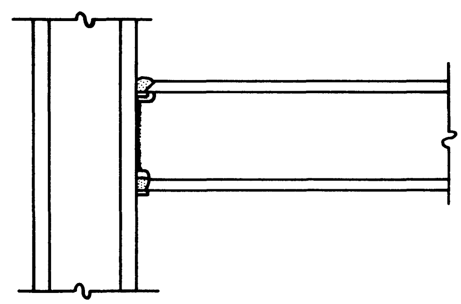


Fig. 12. Web welds and the thick column flanges provide high restraint to the contraction of large flange welds. Large unit strains are forced to concentrate in column flange opposite beam flange welds.

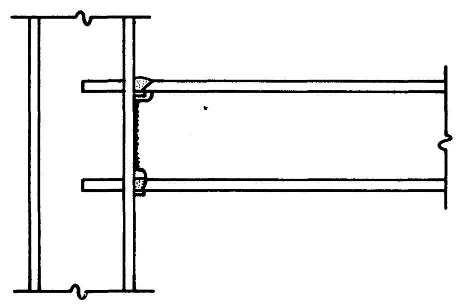


Fig. 13. Web welds and stiffened thin column flanges also provide high restraint to contraction of flange welds.

2. When a heavy full penetration weld is made close to the edge of a thick plate, as in a heavy box column (Fig. 14) or a welded connection of a heavy base or cap plate to a column (Fig. 15), high restraint can result. This occurs when tension (*T*) due to weld contraction is resisted by compression (*C*) developed in previously deposited weld metal, as is common in multi-pass welds.

3. Tight fit-up in weldments can result in a critical restraint mechanism when the weld contraction tensile forces are resisted by compressive forces in the area of tight fit-up. (See Figs. 16 and 17.)

4. If fit-up clearance in weldments is provided with large multi-pass welds, the root pass may restrain the joint and induce high tensile forces opposite the finish passes (Fig. 18).

5. Full member restraint develops when a fill-in member has to be welded between rigid assemblies, resulting in closure welds made under high restraint (Fig. 19).

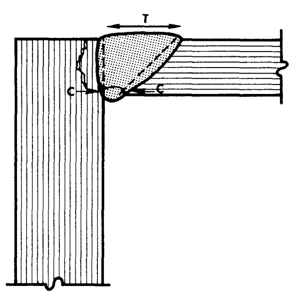


Fig. 14. Placing large welds close to the edge of a plate, as in the corner of a box column, increases susceptibility to lamellar tearing.

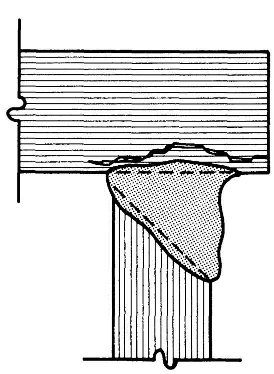


Fig. 15. Large volumes of weld metal increase susceptibility to lamellar tearing.

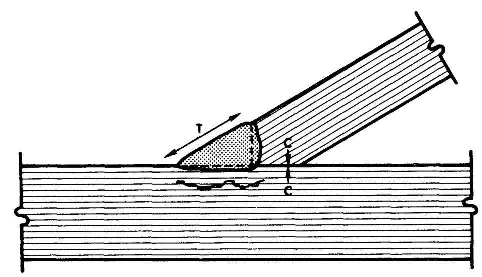


Fig. 16. Example of fit-up restraint with large single fillet weld

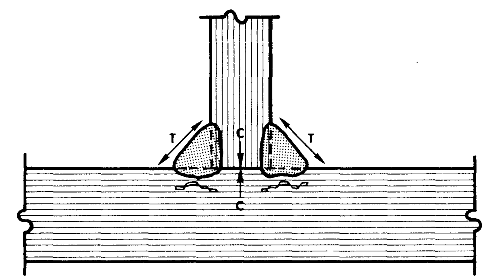


Fig. 17. Example of fit-up restraint with large double fillet welds

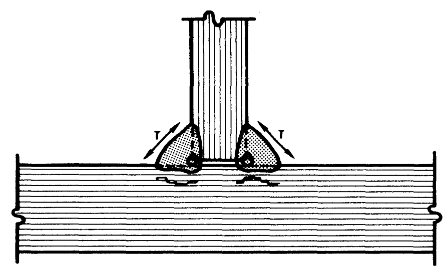


Fig. 18. Root passes of multiple pass welds restrain tee joints even when fit-up clearance is provided.

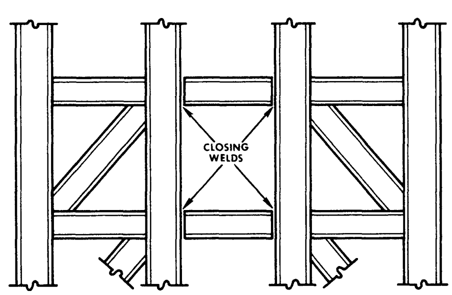


Fig. 19. Closing welds for members between rigid assemblies are subject to high restraint.

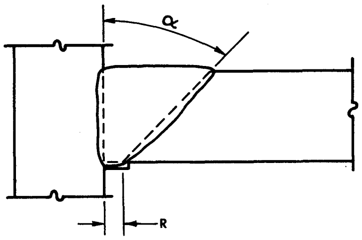


Fig. 20. Prequalified joints, such as AWS TC-U4a above, do not insure freedom from lamellar tearing.

WELD DESIGN, WORKMANSHIP, AND TECHNIQUE

Use of a prequalified joint (for example, Fig. 20) does not insure that freedom from lamellar tearing will be obtained when the connected parts are highly restrained during welding and subsequent cooling. AWS prequalified joints were developed to establish joint geometries and procedures that will produce sound weld metal with appropriate mechanical properties. The effect of weld contraction on the connected material under conditions of high restraint is not included in prequalification tests. The effects of restraints provided by a complete assembly (as contrasted to unrestrained test plates) may result in higher strains than can be accommodated by the parent material.

The size of the weld nugget has an important effect on the total amount of strain which must be accommodated in the connection. A wide groove angle increases the width of the weld surface and, therefore, the shrinkage strain. One-sided groove welds build up unsymmetrical shrinkage strains throughout the entire thickness of the joint, whereas double groove welds reduce and balance shrinkage strains. However, weld groove geometry must be selected with full recognition of practical considerations of feasibility and economy. For material thicknesses up to approximately ¾-in., the use of double bevel in lieu of single bevel welds will not significantly reduce the total weld contraction to be accommodated, due to the minimum size groove required to deposit sound weld metal. Many double bevel welds would require out-of-position welding or difficult and expensive turning of material to permit downhand welding. Thus, selection of groove geometry demands intelligent evaluation of all factors. The arbitrary requirement of double bevel welds for all cases is an ill-advised procedure.

Welds which are larger than those required to carry design loads (sometimes arbitrarily selected on the assumption that the larger and more complete the weld, the stronger the joint) will unnecessarily increase shrinkage strains. The unnecessary use of full penetration groove welds in place of properly sized fillet welds can contribute to lamellar tearing.

Minimum size fillet welds complying with AWS Specification requirements, which are based upon judgment consideration of the chill effect of material of various thicknesses, can be in excess of those required to carry design loads. Tests have shown that sound welded joints using smaller welds can be made providing proper procedures, including preheat, are followed.

The possibility of lamellar tearing may be increased if weld sequences are not planned to minimize contraction strains, restraint, and distortion. The effect of high shrinkage strains in welded joints can be minimized by certain welding techniques. Among these are *buttering*, the *stringer bead* technique, and *peening:*

Buttering takes advantage of the more uniform and isotropic properties of deposited weld metal to enable the welder to build ductility into a highly restrained joint. Generally a low yield strength electrode is used for this purpose (Fig. 21a).*

The *stringer bead* technique is useful in filling in large preparations. Proper sequence of weld beads assists in controlling contraction to minimize the accumulated strain (Fig. 21b).

Controlled *peening*, as outlined in AWS D1.1-72, can be used to reduce the stresses in multi-pass welds (Fig. 21b).

* *Figures 21 through 28 are representative only and are not intended to be specific recommendations to be used without consideration by the designer of all factors which bear on the specific connection.*

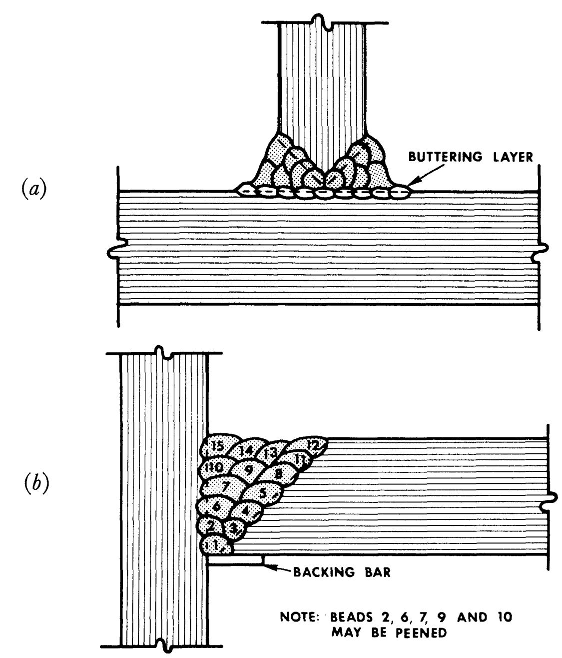


Fig. 21. Properly sequenced stringer beads permit unrestrained contraction of individual weld beads, when large grooves must be filled. Controlled peening of certain passes further reduces the tensile strains. (Root pass 11 and cover passes 12, 13, 14, and 15 should not be peened.)

Buttering, stringer bead, and peening techniques increase cost and should be used only when required for successful completion of the connection.

The effect of preheat on lamellar tearing is not well understood. However, the use of appropriate preheat and the maintenance of interpass temperatures are important to the welding process for considerations other than lamellar tearing, and there is some evidence that they can have a beneficial effect on minimizing lamellar tearing.

INSPECTION

Inspection of highly restrained heavy welded joints which are critical to the performance of the completed structure is important for quality control during fabrication and erection, or evaluation of the completed joints. To assure that quality consistent with the end use is achieved, inspection requirements should be objective and appropriate to the particular connection and stage of the work. Meaningful inspection can result only from intelligent selection of the extent and method of test followed by execution and evaluation of the inspection by qualified personnel. Over-inspection is costly and is not necessarily productive.

In the event that lamellar tears are identified, rational consideration should be given to the best action to be taken. The arbitrary requirement that the tears be cut out and rewelded, possibly under conditions of even higher restraint than in the initial work, will likely produce new tears if the procedures are not modified. In some cases, the best solution may be to change the detail. In other cases, an evaluation of the tears relative to the service conditions may indicate that lack of perfection is not detrimental to the structural safety of the connection.

The most suitable non-destructive inspection technique for the detection of lamellar tears in completed highly restrained welded joints is ultrasonic testing (UT). (Radiographic examination is of little value in detecting lamellar tears.) The designer should *not* specify UT quality material or ultrasonic inspection of plain material *before* fabrication in the mistaken belief that such inspection—or any other existing type of non-destructive testing—can effectively evaluate the *susceptibility* of steel to lamellar tearing. UT can effectively reveal gross discontinuities, such as large non-metallic inclusions; however, it cannot reveal microscopic inclusions that can also lead to lamellar tears. Such testing only adds cost without providing assurance that the completed joints will be sound.

The designer should determine those highly restrained heavily welded joints included in the design which are critical to the integrity of the structure. UT of these joints should be considered and, if required, clearly stated in the invitation to bid. However, it is a fact that, under the existing state of the art, definite rules cannot be stated which will assure that lamellar tears will not occur. As emphasized throughout this paper, in any specific case, lamellar tears may result from one or more contributing factors. Therefore, if tears occur, the decision by the designer on action to be taken should involve consideration of the structural significance of the discontinuity, and review of all factors which possibly have contributed to the development of the discontinuities. Simply cutting out the discontinuity and rewelding, using originally specified joint geometry and procedure under conditions of possibly even higher restraint, will probably result in new lamellar tears being formed.

RECOMMENDATIONS

Successful highly restrained connections require an understanding of the phenomenon and attention to detail on the part of the designer. Good materials and workmanship cannot assure success on poorly conceived and designed or specified connections.

Any hot rolled structural steel may be susceptible to tearing when stressed in the thru-thickness direction by highly restrained welds. Therefore, it is important to provide relief in the form of ductility, linear movement, or deformation to relieve localized strains. Lamellar tearing is most frequently associated with large groove welds which are generally required with thick material; therefore, it has been mistakenly presumed that lamellar tearing is only a problem in thick material. If the groove weld size or restraint condition is sufficient, it can also occur in thin material. Therefore, the designer should exercise care in design regardless of the material thickness involved.

The applicability of one recommendation rather than another will depend on a particular application and will involve the independent examination of the relevant factors. The following are some recommendations presented as representative of possible means to minimize or avoid lamellar tearing:

1. Select electrodes which deposit weld metal with the lowest yield strength adequate to carry design loads. The use of excessively high yield strength weld metal can force strains above yield point in the connected material.

2. Design connections to minimize accumulation and concentration of strains resulting from weld metal contraction in localized areas. Figures 22, 23, and 24 show moment connection details that are designed to allow dissipation of shrinkage strains from full penetration flange welds. These connections have a low incidence of lamellar tearing. Figure 25 shows how material subject to high strain in the thru-thickness direction can sometimes be eliminated by redesign of the connection.

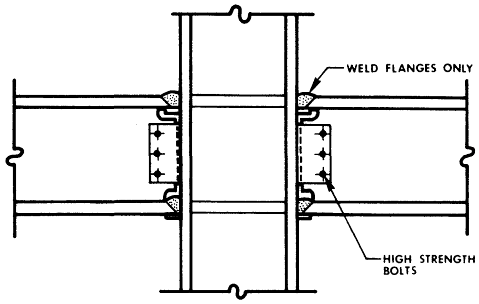


Fig. 22. Moment connection using shear connection plate. High strength bolted web connection allows flange weld shrinkage strains to be relieved.

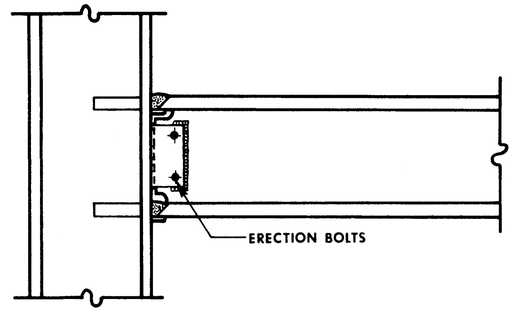


Fig. 23. Moment connection using shear connection plate. Welding plate to web after completion of flange welds avoids high shrinkage strains.

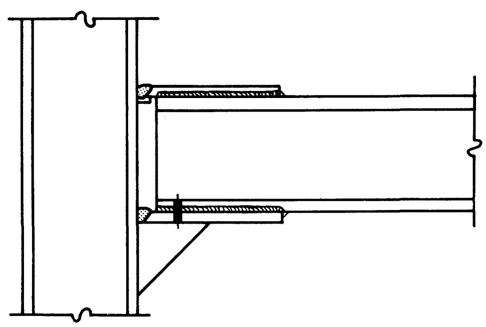
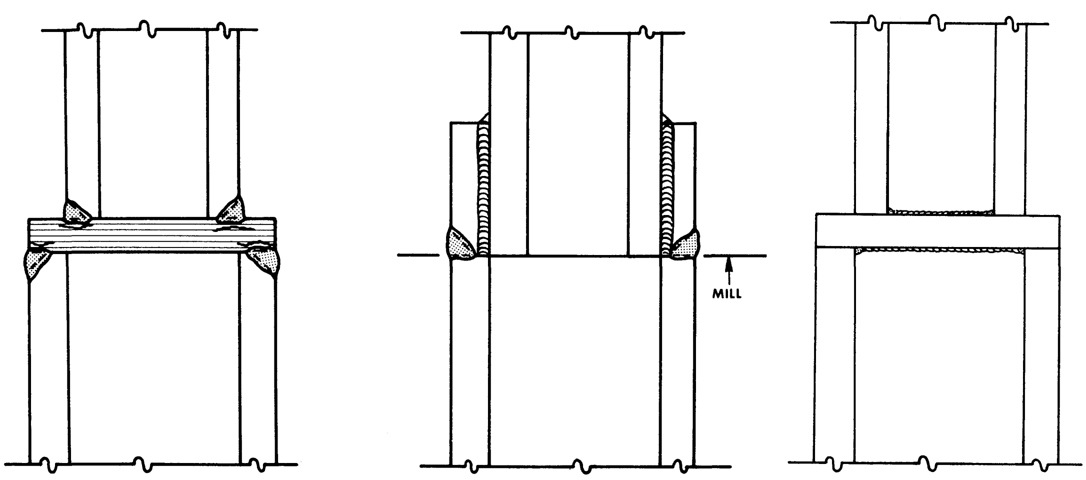


Fig. 24. Moment connection using flange connection plates. To avoid high shrinkage strains, beam seat is shop welded to column; top plate weld to column is made in field, followed by fillet welds of top and bottom plates to beam flanges.



Susceptible detail *Improved detail* *Improved detail*

Fig. 25. Material susceptible to lamellar tearing can be eliminated by redesign of a connection.

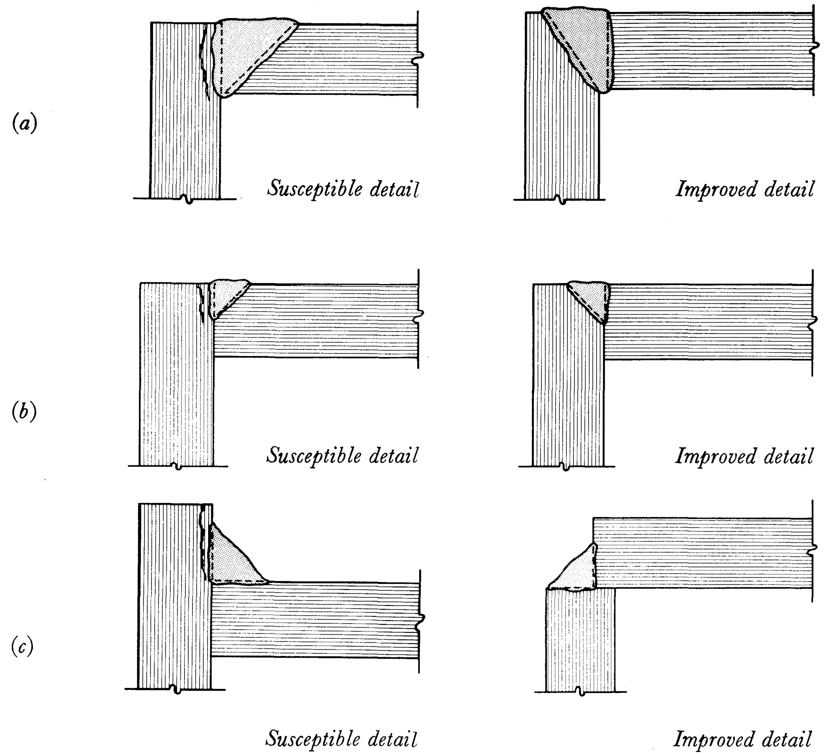


Fig. 26. Susceptibility to lamellar tearing can be reduced by careful detailing of welded connections.

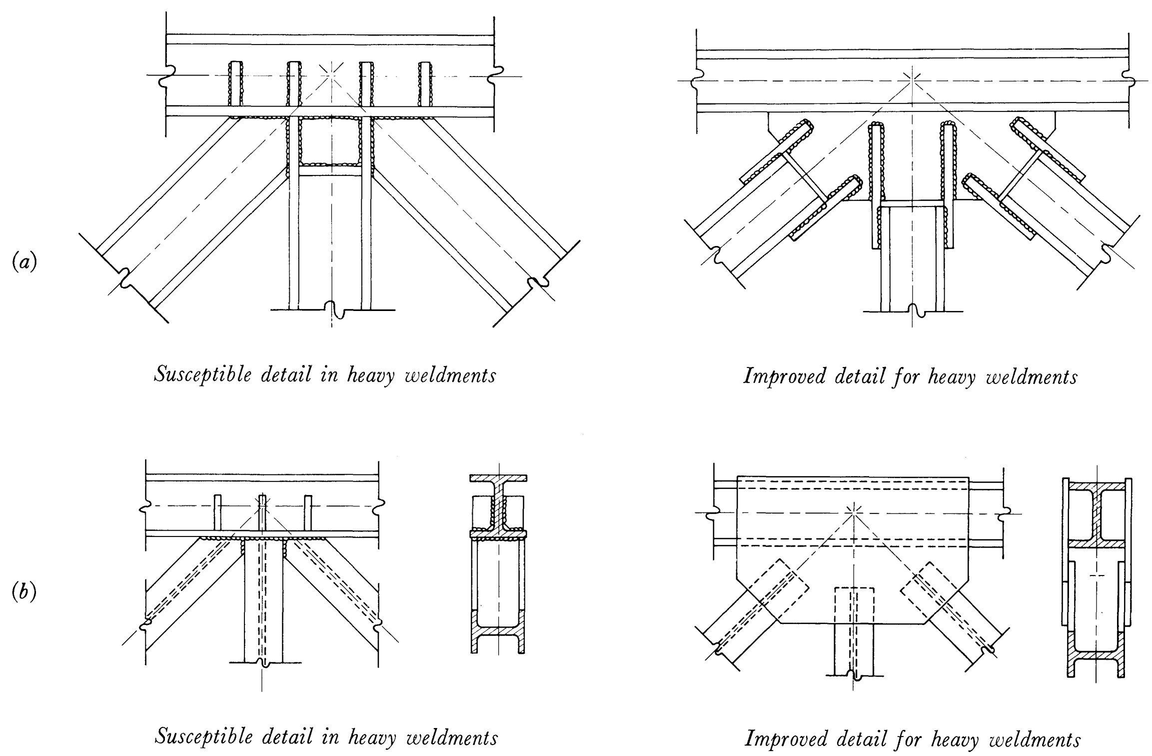


Fig. 27. In many cases large complex highly restrained connections can be redesigned to minimize or avoid joints which induce weld shrinkage strains in the thru-thickness direction of the connected material.

Figure 26 compares details having a high incidence of lamellar tearing and details where the thru-thickness is engaged to minimize the probability of tearing.

3. Where possible, arrange connections so as to avoid welded joints which induce thru-thickness strains due to weld shrinkage (Fig. 27).

4. Make connections with welds having the minimum throat dimension required to carry the stresses and having a minimum practical volume of weld metal. Lower strength fillet or partial penetration welds may often be used to join higher strength steels when the joint is designed for shear.

5. Design corner joints with proper consideration of edge preparation. (See the improved details in Figs. 26a, b, and c.)

6. Consideration of the use of soft wire cushions or other means to permit contraction of weld metal without producing high concentration of stresses may be helpful in difficult situations (see Fig. 28).

7. Whenever practical, completely weld subassemblies prior to final assembly of the connection. Sequence the welding of individual joints so that restraints will be minimized on the largest welds. Tack welds should be limited to a minimal size and number.

8. Do not arbitrarily use prequalified joints without considering restraints provided by the complete connection assembly.

9. The designer should fully research and utilize available experience and knowledge on specific design details that might be potential sources of lamellar tearing.

10. Do not use larger welds than are necessary to transfer calculated forces.

11. Do not specify stiffeners when they are not required by design calculations. Stiffeners induce restraint. When stiffeners are required, make them and the welds by which they are attached only as large as required by calculations.

12. Before making repairs to highly restrained connections, determine whether the repair will be more detrimental than the original cause for repair. Usually a repair must be made under greater restraint than the original weld. It is often better to tolerate a minor imperfection than to create conditions that will cause a lamellar tear. If the discontinuity is a lamellar tear, consider the modifications to the welding procedure or the details which are needed to avoid reoccurrence of lamellar tears in the repaired connection.

13. The designer should selectively specify ultrasonic inspection *after fabrication and/or erection* of those specific highly restrained welded connections critical to structural integrity that he considers to be subject to lamellar tearing.

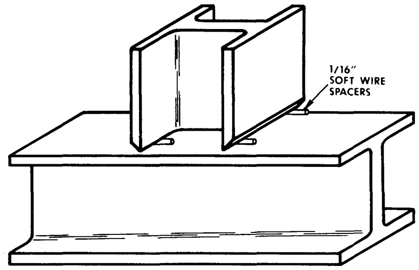


Fig. 28. Soft wire spacers permit welds to contract without inducing high strains in connected material.

CONCLUSION

The design of highly restrained welded connections must take into account the material properties and performance when subjected to conditions of high restraint and shrinkage of large welds.

Finally, it should be stated and emphasized again that the great majority of welded connections are not subject to conditions that induce lamellar tearing. Since this is a fact, the purpose of this paper is to present information that will aid in avoiding conditions that might lead to lamellar tearing in the limited number of connections where its occurrence could have structural significance.

GLOSSARY OF TERMS

Anisotropic	Not isotropic, i.e., having different mechanical properties in different directions
Decohesion	Separation of steel matrix at grain boundaries
Discontinuities	Lack of homogeneous characteristics caused by nonmetallic inclusions, cracks, tears, etc.
Ductility	Ability of a material subjected to stress to undergo permanent deformation in the plastic range prior to rupture
Elongation	Percentage elongation measured in a standard tension test and used as a measure of ductility
Isotropic	Having the same mechanical properties in different directions
Lamellar Tearing	Separation in the parent or base material caused by induced strains in the thru-thickness direction due to weld shrinkage

Lamination	Discontinuity in rolled steel products resulting from flattening and elongating of inclusions or voids during the rolling process
Mechanical Properties	Tensile strength, yield strength, percentage elongation, etc. (General minimum requirements are specified by references to ASTM specifications.)
Non-metallic Inclusions	Microscopic particles of compounds in steel matrix, principally sulphides, silicates, and aluminum oxides
Parent Metal	Basic mill-rolled material being fabricated
Preheat	Heat applied to the parent metal prior to welding
Reduction in Area	The percentage reduction in cross-sectional area measured in a standard tension test at point of rupture and used as a measure of ductility
Rolling Direction	Direction that hot rolled structural material travels through the forming rolls (Fig. 3)
Strain	Deformation due to changes in applied forces
Stress	Force per unit of area
Tensile Strength	Maximum stress required to rupture the material
Thru-thickness	Perpendicular to the plane of the rolled surface (Fig. 3)
Transverse	Perpendicular to the rolling direction in the plane of the material (Fig. 3)
UT Material	Material ultrasonically inspected in its entirety prior to fabrication
Yield Point	The stress at which yielding occurs for those steels that have a "sharp-kneed" stress-strain diagram or the yield strength as determined by the "offset method" for those steels that do not have a "sharp-kneed" stress-strain diagram

Welding

Electrode Strength	Commonly the minimum tensile strength of deposited weld metal
Electrode Matching	The practice of providing electrode strength equal to parent metal tensile strength
Heat Affected Zone	Zone of the parent metal adjacent to fusion line of weld, which is heated to a temperature high enough to modify the microstructure
Interpass Temperature	Weld area temperature during time between actual deposition of weld metal passes
Manual Electrodes	So called "stick" electrodes, coated with flux and used for shielded metal-arc welding
Multi-pass Welds	Welds requiring more than one pass to complete deposition of required weld metal
Peening	Mechanical strain-relieving of weld metal by striking a series of light blows, generally with air actuated peening hammer
Prequalified Joint	An AWS approved joint design giving edge preparation, root opening, thickness, and other details that have been proven by experience to permit deposition of sound weld metal with appropriate mechanical properties
Welding Procedure	Written procedure defining voltage, current, speed, electrode type and size, position, edge preparation, preheat and any other related factors required for an acceptable quality weld
Welding Sequence	The order in which welds are made in a particular weldment to minimize distortion, compensate for shrinkage and reduce internal strains.

Connections and Joints

Component Restraint	Restraint existing because of rigidity of various elements of a joint or connection
Connection	Complete assembly consisting of the various joints making up the total unit
Joint	A single element of a connection
Member Restraint	Restraint in closure member where inherent rigidity requires weld shrinkage to be absorbed by the parent metal
Preparation	Geometry of a joint detail including edge bevel, root opening, backup, and land details
Restraint	Resistance of the joint or connection to weld shrinkage strains

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DISCUSSION

Commentary on Highly Restrained Welded Connections

Paper presented by American Institute of Steel Construction (3rd Quarter, 1973)

Discussion by **Norman B. Jones**

The commentary by the American Institute of Steel Construction was a most welcome initial compilation of information regarding the very timely subject of lamellar tearing of welded connections. Numerous helpful suggestions are presented throughout the article, but the writer believes that the concern of the members of the design profession has been underestimated. Surely something more definitive and quantitative can be done to insure the statement in the Conclusion that "the great majority of welded connections are not subject to conditions that induce lamellar tearing."

In late July, 1973, it was reported that extensive lamellar tearing had appeared in transmission tower joints where "the tower plates ranged from only ⅜- to 1$\frac{1}{16}$-in. thick."[1,2] The illustration given of the original design details pointed out a tear location in a plate only ½-in. thick. Little wonder that the same publication later reported a case where designers of a 32-story building had elected to use all-bolted connections for the framing.[3]

In order to use the many applications customary for the welded joint illustrated in Fig. 22, we need better guidelines to insure that we will be safe from lamellar tear possibilities. Are there actually definite thicknesses of column (or beam) flanges where tearing is not a problem? Are the suggestions noted in Fig. 21 reasonably economic, and at what thicknesses should they be required? Is there a sequence or procedure for shop welding the stiffeners of Fig. 22 that might reduce restraint for the field welding of the connecting flanges? Is preheat before such field welding helpful in reducing tear possibilities? For what thicknesses of flanges? Are rolled flanges more or less susceptible to lamellar tear than plates?

As these few questions indicate, the writer hopes that there may be available considerably more helpful and definitive information than was included in the commentary. There could be no mistake in making such quantitative detailed information available to the design profession as rapidly as possible.

Norman B. Jones is Chief Structural Engineer, Holmes & Narver, Inc., Anaheim, Calif.

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Discussion by **W. A. Milek**

The discussion by Mr. Jones expresses the questions of many designers relative to the phenomenon of lamellar tearing and his comments are appreciated. Unfortunately, definitive answers to the deceptively simple and clear questions are not available under the present state of engineering knowledge. It was exactly because of the fact that no way has been found to quantify the individual effects of the many factors involved that the Committee prepared a summary of general information derived from research reports that were available from around the world, rather than a compendium of specific recommendations.

The intent was to give designers and fabricators alike a general understanding of the mechanics of the phenomenon and a recognition of the fact that the many factors that bear upon the problem must be considered together; each considered separately can either ameliorate or compound the tendency for tears to develop. No solution dealing with a single factor, nor with a combination of several factors, can be counted upon to provide a guarantee that difficulty will not be encountered in susceptible connections.

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Even though some new information has been developed as a result of considerable research effort since the Commentary was published, definitive (quantitative) answers to the stated questions should still be avoided, since such answers might be erroneously construed as implying some guarantee of a solution for specific cases. Honest questions deserve honest answers; therefore, the following comments are offered in an attempt to be responsive, but with full recognition that definitive answers cannot be given.

Q. "Are there actually definite thicknesses of column (or beam) flanges where tearing is not a problem?"

A. In the context that definite thickness means a threshold thickness below which no consideration of the potential for lamellar tearing exists, the answer is "no." Thickness of material is indirectly related to the potential for lamellar tearing. Tears are caused by contraction due to cooling of solidified weld metal under conditions of high restraint. The larger the weld nugget, the greater will be the shrinkage that must be accommodated. Since there is generally some proportionality between size of weld deposit and thickness of material, tearing is more often encountered in thicker materials, but the magnitude of weld contraction to be accommodated, rather than material thickness *per se*, is the important factor. Similarly, although the restraint is related to thickness in many cases, heavily stiffened thin material can also provide restraint equivalent to that of unstiffened thick material. Practical experience has shown that lamellar tearing is a highly unlikely phenomenon in material less than ¾ to 1 in. in thickness, even though a few instances involving thinner material have occurred, as Mr. Jones points out. In laboratory research on joints restrained so as to intentionally produce lamellar tears, it has been observed that tears are not initiated until 4 or 5 weld beads have been deposited and cooled. Thousands of buildings, each using many connections typical of those shown in the AISC Manual, have been built with beams and columns of the frequently used sizes without developing lamellar tears. Beyond these comments, it would be imprudent to suggest specific guidelines.

Q. "Are the suggestions noted in Fig. 21 reasonably economic, and at what thickness should they be re quired?"

A. Yes, they are economic if rework is avoided. No, they are not economic when used where not required. Sequencing of weld beads, buttering, and peening are workmanship techniques which should be under the control of the fabricator and his welding engineer. In general, contract specifications should avoid stipulating "how to do it" provisions, since if step-by-step procedures are established by the contract the designer must be willing to accept the responsibility if success is not achieved. Designers should specify details which will cause a minimum of weld contraction and minimum restraint to the contraction; the fabricator should use his experience and technical knowledge and various workmanship techniques to minimize the effect of the strain and restraint conditions that result from the connection design.

Q. "Is there a sequence or procedure for shop welding the stiffeners of Fig. 22 that might reduce restraint for the field welding of the connecting flanges?"

A. Stiffeners themselves can contribute significantly to restraint, but variations in the shop welding procedures for such stiffeners will probably have little bearing on the restraint to the contraction strains of the field welds at the outside face of the column flange. It must be remembered, however, that, independent of field welds, a potential for producing lamellar tears at the inside face of the column flanges does exist. Stiffener and weld details and welding procedure can significantly affect this possibility. Stiffeners may be required for one or more of three reasons: (1) to prevent crippling at the toe of the fillet [AISC Spec. Formula (1.15.1)]; (2) to prevent general buckling of a thin column web [AISC Spec. Formula (1.15.2)]; or (3) to prevent localized overstress of beam tension flange welds when the column flange is thin [AISC Spec. Formula (1.15.3)]. Only for the third case is a weld between the stiffener and the column flange actually required. In any event, welding of stiffeners to columns should be by means of fillet welds. Full penetration stiffener welds can be justified only in the case of a true fatigue condition, which is highly improbable in building construction.

Q. "Is preheat before such field welding helpful in reducing tear possibilities? For what thickness flanges?"

A. Probably yes. Laboratory tests have indicated that preheat and interpass temperatures do have a beneficial effect. See Oates and Stout, *Welding Journal*, November 1973. However, systematic investigation of the effect of preheat temperatures is still underway, and it is conceivable that this work may lead to specific recommendations. In any event, proper preheat and interpass temperatures are important for the deposition of sound welds for reasons independent of possible beneficial effect on tearing; thus, specification requirements should be adhered to. It is not known whether preheat and interpass temperatures higher than those presently specified are most beneficial.

Q. "Are rolled flanges more or less susceptible to lamellar tear than plates?"

A. No difference. Lamellar tearing results from inevitable contraction strains due to cooling of solidified weld metal in the presence of high restraint which forces the total strain to concentrate within an extremely short gage length. Thus, the unit strains may be many times larger than even longitudinal yield point strains for the base metal. When connected parts meet in a tee configuration, a triaxial state of stress is induced at the face of the head of the tee. Under these circumstances, the longitudinal strain in the direction of the stem of the tee tends to force a volumetric change in the head of the tee which any solid material cannot accept to a practical degree.

Even in the presence of known lamellar tears which were intentionally initiated, externally applied stresses necessary to cause fracture have been observed to be several times higher than full allowable design stresses (Oates and Stout, Welding Journal, November 1973). This demonstrated fact is not surprising and should be a source of comfort to designers, because the forced strains due to weld shrinkage in the presence of high restraint are at least one order of magnitude larger than the strains that are introduced by design stresses. Stresses due to applied design loads will not initiate lamellar tears. Stresses due to static applied design loads probably will not propagate tears that inadvertently are not detected by ultrasonic testing. Because lamellar tears occur infrequently, but always during fabrication or erection at a time when they may be detected and corrected, and also do not result from design stresses which may induce stress in the through-thickness direction, they should not be a source of major concern.

The geometry of joints and connections is the most important and controllable factor that influences the phenomenon. All other factors can only ameliorate or compound the tendency toward lamellar tearing once the restraint and strain from weld contraction are established by the arrangement and size of connected parts. Maximum attention should be given to avoiding susceptible details wherever possible.