Quality Control in Design and Supervision Can Eliminate Lamellar Tearing

CHARLES H. THORNTON

In the last few years, the design professions and the construction industry have experienced the occurrence of a pheomena called *lamellar tearing* in highly restrained joints within welded connections. Actually, the term "highly restrained" is relative; lamellar tearing can occur in connections which provide any degree of restraint to the connected members, but the restraint that is responsible for lamellar tearing is the localized restraint to contraction of individual welds.

Lamellar tearing in steel is defined as a separation initiating in the parent or base material caused by thru-thickness strains induced by weld metal shrinkage. Due to the rolling process, plates and rolled members possess a lower ductility in the thru-thickness direction than parallel to the direction of rolling. This lower ductility, which is influenced by the presence of microscopic, non-metallic inclusions oriented in the direction of rolling, causes lamellar tearing when high thru-thickness strains are induced due to cooling and shrinkage of restrained welds. Recent design trends toward high strength steels, namely ASTM A572 and A588, and more sophisticated structural analyses which place higher demands on the material have increased the need to avoid occurrence of lamellar tearing. Furthermore, the increased use of welded connections for thick plate weldments and heavy jumbo member sizes also increases the frequency of occurrence of high joint restraint in connections.

RECENT EXPERIENCE WITH LAMELLAR TEARING

Several recent experiences on projects engineered by Lev Zetlin Associates yielded insights into the causes and circumstances surrounding the occurrence of lamellar tearing in steel framed structures. The circumstances include:

Charles H. Thornton is Senior Vice President—Engineering, Lev Zetlin Associates, New York, N.Y.

1. The use of highly restrained welded connections.
2. The use of thick, high strength steel plates and members.
3. Inadequate welding design and poor sequence for welding highly restrained joints.
4. Incorrect and inadequate use of preheat and maintenance of interpass temperatures.
5. Inadequate controlling of the cooling process after the weld is completed.
6. Inadequate quality control at every stage of the fabrication process for critical joints.
7. Specification of full-penetration welds where fillet welds would suffice from strength considerations.

Several LZA projects in the late sixties were prototypes, of which more than one was constructed in different locations in the U. S. Since these prototype buildings were constructed in different locations, different steel fabricators and erectors were used on each project. This set of circumstances and the resulting experience allowed us to evaluate the reasons why, in one case, a project was successfully fabricated and erected with no occurrence of lamellar tearing and, in another case, for the same structural design, the fabrication and lack of development of good weld procedures, details, and implementation produced lamellar tearing. An example of one connection in which lamellar tearing occurred is shown in Fig. 1.

The successful fabricator, through his in-house quality control, had developed good welding procedures, closely supervised and monitored his welding operations, utilized ultrasonic testing (UT) for scanning all plate material at tee-type welds prior to welding, utilized electroslag welding when heavy welds in thick plates were needed, used controlled peening to reduce stresses in multi-pass welds, and redesigned joints to reduce occurrences when weld shrinkage could cause thru-thickness strains. In summary, the successful contractor

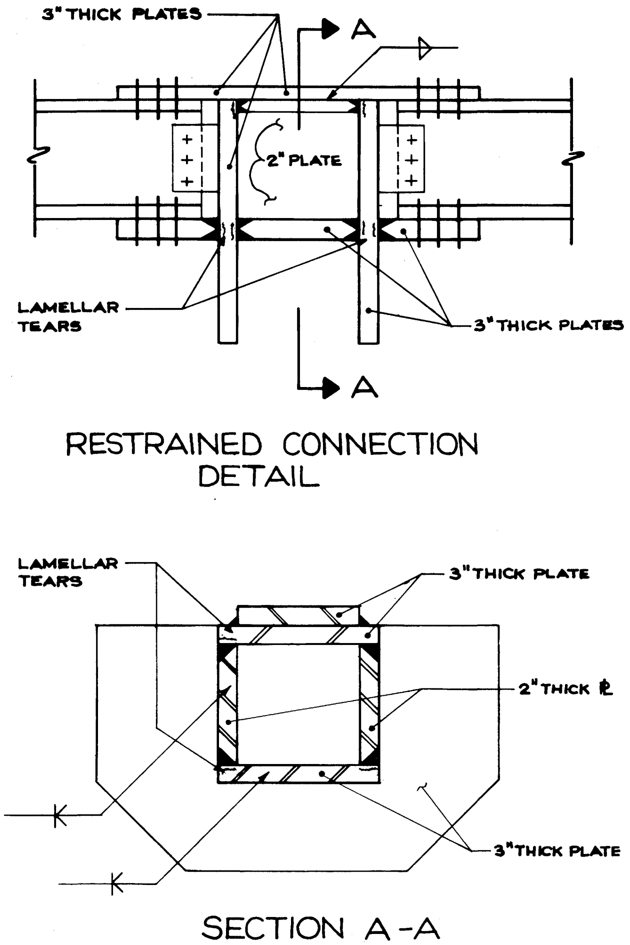

Fig. 1. Restrained joint connection in which lamellar tearing occurred

had his own in-house quality control in addition to the inspection and supervision provided by the owner and engineer.

In our experience, a fabricator with previous experience with highly restrained welded connections and previous experience with lamellar tearing has been better equipped to minimize or control the problem, since he had lived through the bad experience of having lamellar tearing occur on a steel structure project.

For the above mentioned prototype structure in which lamellar tearing did occur, the structure contained highly restrained connection weldments for large trusses fabricated of 3-in. thick ASTM A588 and A572 material. The fabricator's quality control for the structural steel work was not up to the standard expected by AISC, AWS, and ASTM. The main reason for this lack of control was the distribution of the fabrication to several plants. As a result, there was no central source or single responsibility for quality control. This resulted in different levels of fabrication quality, poor welding techniques, and poor controls on the welding process. The lack of quality control allowed the welds to be made without any UT of the plate material prior to welding and without any preplanning as to welding sequence of temperature controls. The fact that the completed weldments were allowed to cool at a rapid rate also contributed to the problems.

After fabrication was completed, widespread cracking in the parent material was discovered. After reviewing the cracking with welding and metallurgy consultants, it was determined that the cracking was lamellar tearing. It is of interest to note that many of the weldments were inspected by visual and non-destructive testing methods immediately upon completion of the welding. Although this immediate inspection did not detect any cracking in many of the weldments, a subsequent inspection several days later uncovered cracking in almost every weld in the highly-restrained joints. The conclusion to be drawn is that UT testing should occur at least 48 hours and preferably 72 hours after completion of the welding.

The fortunate occurrence concerning the behavior of these weldments was that during the fabrication process all cracks and lamellar tears came to the surface. Therefore, even visual inspection and surface non-destructive test methods, such as dye penetrant or magnetic particle, were useful and adequate to detect the presence of cracks due to lamellar tearing. This does not in any way suggest that ultrasonic testing should not be used. However, for a first review of fabricated welded members, the surface testing methods such as dye penetrant and magnetic particle should be used in order to detect whether there is any cracking or lamellar tearing present.

After the cracking was discovered, repair procedures were developed in which all cracks were gouged out and repaired with new weld metal. However, because of the highly restrained configuration and the already-present residual stresses, the cracking continued to plague the weldments. It was finally decided to stress-relieve all weldments in high temperature ovens, after which all remaining lamellar tears were removed and repaired successfully. All connections were then successfully utilized in the project.

NIAGARA FALLS CONVENTION CENTER

Based upon the above experience, we formulated quality control procedures and practices for all projects with restrained welded connections. These procedures have been highly successful and are now our standard course of practice for projects.

A project which immediately followed the previously discussed project is the Niagara Falls Convention Center. The Niagara Falls Convention Center is a 450,000-sq-ft multi-purpose convention and exhibition building located in Niagara Falls, N. Y. The project, owned by the City of Niagara Falls, is financed through the New York State Urban Development Corporation. Architect

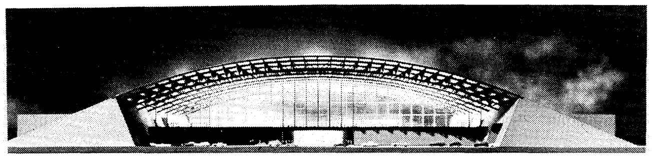

Fig. 2. Niagara Falls Convention Center

for the project was Philip Johnson and John Burgee, New York, N. Y., Associate-in-charge for Lev Zetlin Associates was Jagdish Prasad.

The building measures 512 ft x 600 ft in plan and contains a shallow long-span arch system spanning 364 ft. Four of the trusses, exposed on the outside, are fabricated of ASTM A588, Grade 50 weathering steel. The remainder of the trusses, which are in the interior, consist of A36 steel. Much of the support structure in the two side abutment areas also contains heavy long span trusses and plate girders, with heavy welded connections in many cases. The project, which is shown in Figs. 2 and 3, was topped out in August, 1972, and completion of the project is scheduled for June, 1974.

Because of the desire to keep all exposed connections as uniform and aesthetically pleasing as possible and also to minimize cost, the use of welding as the major method of connection for the trusses was specified. Most of the members within the trusses and the support structure contain thick plates varying from 2 to 4 in. in thickness. As a result, many of the connections are classified as restrained and, therefore, can potentially develop high residual stresses. The project was approached with a three phase effort in order to assure a successful project and to minimize the potential of lamellar tearing.

The phases were as the follows:

Phase 1: Review of design and details to pinpoint potential problem areas.

Phase 2: Development of tight specifications and a quality control program with the successful contractor.

Phase 3: Continued inspection and monitoring for quality control of the fabrication and construction for the duration of the project.

With these three phases successfully undertaken, we achieved a successful project with virtually no defects and welding problems.

Phase 1—During the design, it was concluded that ASTM A588 weathering steel should be utilized for the trusses located outside of the enclosed convention area. Because of the requirements for the 364-ft span, it was necessary to utilize plate thicknesses greater than 1½ in. Through the combination of A588 steel and thick plate configuration, we anticipated that lamellar tearing could be a problem.

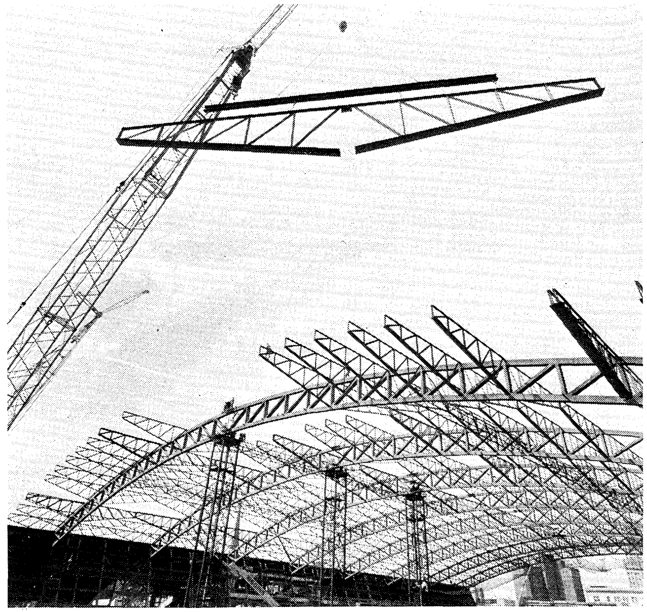

Fig. 3. 365-ft all-welded arch truss during erection of the building

Extreme care was taken in the design and the development of details in order to achieve connections in which the shrinkage or cooling of a weld would cause strains in the plates as close to parallel to the direction of rolling as possible. Typical connections which were developed are shown in Figs. 4a and b. In all of these cases, it should be noted that the weld is placed in such a way as to cause shrinkage strains to induce strains either parallel to the direction of rolling or always less than 45° to the direction of rolling. Care was taken where stressing occurred perpendicular to the grain or at an angle greater than 45 degrees. Attention was paid to connections to minimize the restraint of the joints within the connection, as shown in Fig. 5. Note that the web of the vertical and diagonal members is not connected to the web of the top and bottom chord. There are many situations in which the configuration of the structure dictates connections which contain highly restrained joints. For this case the quality control of the fabrication process becomes the main deterrent to lamellar tearing.

Based upon our previous experience, we also developed connections and specified the minimum size weld required in order to adequately transfer the design stresses through the connection. Experience has shown that arbitrarily increasing welds from heavy fillet welds to full penetration welds and indiscriminate use of full penetration welds can be a poor practice. The larger the amount of weld material deposited, the greater the chances of having thru-thickness lamellar tearing.

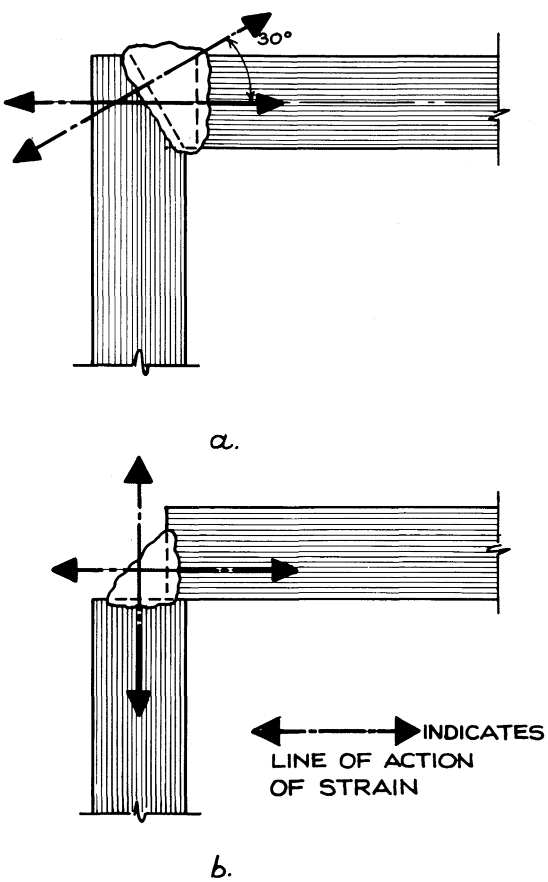

Fig. 4. Details which reduce thru-thickness strains

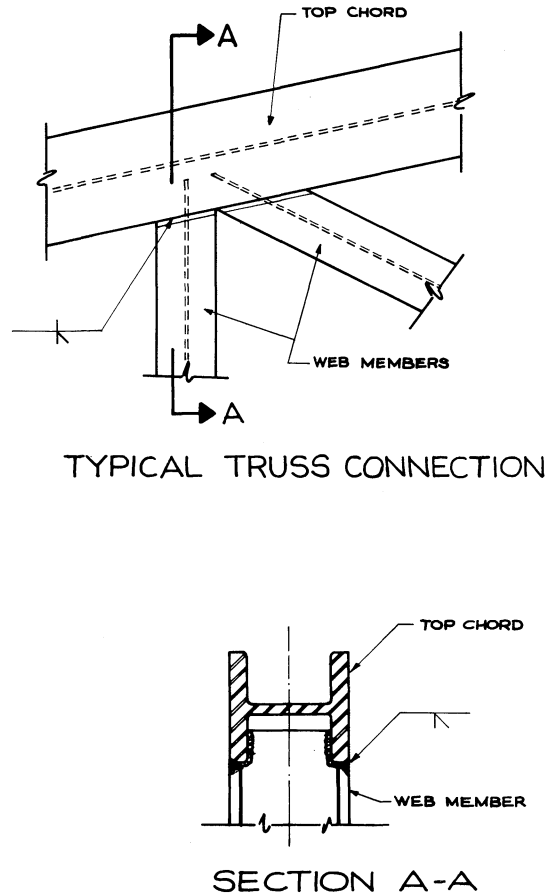

Fig. 5. Welded truss joint detail

In addition, the type of electrode to be specified was selected based upon its compatibility with the material utilized in the truss members. The development of all details and the necessity of stiffeners were also well thought out. The presence of stiffeners, which many assume provides a safer connection, actually causes many problems. Stiffeners tend to occur in the web between the flanges which, when the cooling of the weld occurs, tends to set up high residual stresses. This can actually induce lamellar tearing in the flanges, since these stresses are in a direction through the thickness of the flange plate.

Phase 2—This phase consisted of the specification development and the establishment of quality control procedures formulated during design and to be implemented at the beginning of construction. Specifications were developed which required special ultrasonic inspection of all plate material in the immediate proximity of restrained tee-type connections susceptible to lamellar tearing.

Although there are opinions that ultrasonic testing cannot determine the susceptibility of a piece of material to lamellar tearing, it is our conclusion that the specification of UT for the plate material in the area of restrained connection is wise and should be used by the fabricator as a quality control means. It alerts the contractor to the possibility of a problem in that area. The UT will locate rejectable discontinuities in plate material and laminations due to slag inclusions and other factors, which, if not repaired, are sometimes misinterpreted as lamellar tearing. In general, it is our opinion that the UT of plate material prior to assembly and fabrication of the weldments is a wise, inexpensive investment.

In addition, specifications were written calling for higher preheat and interpass temperatures during welding, with more specific controls on the cooling process after completion of the weld than AWS requires. The rate of cooling in degrees per hour was specified for all critical, restrained connections. Electric blanket-type heaters and asbestos blankets were utilized to control the cooling process. These cooling controls tend to act as stress relief for the connections. The AWS is a general specification and in many cases is a minimum requirement. In our opinion, it is up to the designer to specify the specific requirements for his particular job.

After the contractor was selected, meetings were set up with the general contractor, steel fabricator, and inspection agencies to establish strict quality control procedures to develop welding details, the implementation of the welding procedures, and the degree of inspection required. The inspection became a mutual effort between the quality control procedures of the contractor and the inspection and monitoring procedures of the engineer and the inspection agency. Although quality control is normally the fabricator's responsibility, it is our opinion that for unusual, complex projects the quality control systems of both contractor and engineer should overlap, particularly when highly restrained welded connections are encountered.

Phase 3—The final phase of the program is the actual quality control and monitoring of the fabricating and construction operation. For projects with unusual spans or highly restrained welded connections, it is our opinion that it is important that the engineer has full time supervision of both the field work and shop work. Full time supervision assures constant involvement with and supervision of the testing agencies, in addition to liaison with the quality control operation of the fabricator.

For the Niagara Falls Convention Center, Lev Zetlin Associates instituted several top level meetings with the management and quality personnel from the fabricator, the contractor, and the inspection agency and the owner. Quality control procedures and periodic reports of the progress of the work were frequently scheduled, with discussions focused on those welds requiring special sequences. Special designs and details evolved in order to minimize shrinkage and residual stresses. The qualifications of the ultrasonic (UT) inspectors were reviewed and discussed. The sensitivities to which ultrasonic testing would be measured for different connections was agreed upon. The sum total of all of these activities, meetings, and procedures was the successful erection of the Niagara Falls Convention Center with a minimum amount of difficulty.

CONCLUSION

The Niagara Falls Convention Center represents a project which utilizes the latest state of the art of high strength steels and design techniques, connections, quality control and fabrication, and erection procedures. It is an example that attests to the belief that when the building team works together with the mutual goal of a successful project, the use of high strength steels in highly restrained connections can be successfully utilized without having the problem of lamellar tearing.