BUCKLING COLLAPSE TESTING ON FRICTION STIR WELDED ALUMINUM STIFFENED PLATE STRUCTURES

SHIP STRUCTURE COMMITTEE
2009
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U. S. Coast Guard Assistant Commandant,  
Assistant Commandant for Marine Safety, Security and Stewardship  
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SEPTEMBER 12, 2009

BUCKLING COLLAPSE TESTING OF FRICTION STIR WELDED ALUMINUM STIFFENED PLATE STRUCTURES

This project examined the structures of friction stir welded (FSW) aluminum plates as an expansion of the work completed in SSC-451 titled Mechanical Collapse Testing on Aluminum Stiffened Panels for Marine Applications, where the ultimate limit state of traditional fusion welding was measured. One of the objectives of this study was to measure and collect mechanical tensile fracture and buckling collapse test data of FSW 5000 and 6000 series aluminum stiffened plate structures. Another objective of this study was to compare fabrication induced imperfections plus the ultimate strength performance characteristics of these structures to those welded by fusion welding.

In general, it was found that (1) the tensile strength properties of FSW material were equal to or better than that of fusion welded material; (2) the ultimate compressive strength of FSW structures was about 10 – 20% greater than those of fusion welded structures; and (3) the fabrication induced imperfections in FSW structures were smaller than those made by fusion welding. However, the investigator also encountered problems of delamination at the FSW regions during buckling collapse which indicates that additional research on FSW parameters is necessary.

BRIAN M. SALERNO
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee
### 16. Abstract

The objectives of this study were to develop a mechanical buckling collapse test database for 5000’s and 6000’s series aluminum stiffened plate structures fabricated by friction stir welding and to compare these structures with similar aluminum plate panels fabricated by fusion welding in terms of weld-induced initial imperfections and ultimate compressive strength performance. The trends or benefits found to be associated with the fusion welding and friction stir welding procedures are discussed. The following is a summary of these discussions.

- It is found that the yield and ultimate tensile strengths of friction stir butt-welded aluminum alloys are equivalent or even better than that of fusion-welded aluminum alloys.
- The initial imperfections induced by friction stir welding tend to be smaller than those induced by fusion welding. Thus, the benefits of the friction stir welding procedure in this respect are clear.
- The ultimate strength performance is found to be 10-20% greater in the friction stir-welded aluminum structures than it is in the fusion-welded aluminum structures. This implies that the friction stir welding procedure is certainly superior to the fusion welding procedure in terms of ultimate compressive strength performance, as long as delamination is prevented.
- All of the friction stir-welded test structures however showed delamination in the welded region after or even before the ultimate strength had been reached. This indicates that the fusion welding procedure is superior to the friction stir welding procedure in terms of compressive strength performance in the welded region.
- It is reconfirmed that nonlinear finite element method computations depend significantly on the structural modeling techniques applied.
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Executive Summary

The objectives of this study were to develop a mechanical buckling collapse test database for 5000’s and 6000’s series aluminum stiffened plate structures fabricated by friction stir welding and to compare these structures with similar aluminum plate panels fabricated by fusion welding in terms of weld-induced initial imperfections and ultimate compressive strength performance. The trends or benefits found to be associated with the fusion welding and friction welding procedures are discussed. The following is a summary of these discussions.

• It is found that the yield and ultimate tensile strengths of friction-stir welded aluminum alloys are equivalent to or can be better than that of fusion-welded aluminum alloys, for butt welds. Tensile coupon tests of friction stir lap-welded aluminum alloys are recommended for the future study to discuss the similar trends of tensile properties.

• The initial imperfections induced by friction stir welding tend to be smaller than those induced by fusion welding. Thus, the benefits of the friction stir welding procedure in this respect are clear.

• The ultimate compressive strength performance is found to be 10-20% greater in the friction stir-welded aluminum structures than it is in the fusion-welded aluminum structures. This implies that the friction stir welding procedure is superior to the fusion welding procedure in terms of ultimate compressive strength performance.

• However, all of the friction stir-welded test structures showed delamination in the welded region after or even before the ultimate strength had been reached. The pre-collapse delamination in the welded region can significantly reduce the ultimate compressive strength performance of the structure. This indicates that the fusion welding procedure is superior to the friction stir welding procedure in terms of compressive strength performance in the welded region, particularly when involving buckling and crushing. Further study is needed to investigate the delamination characteristics in the friction stir-welded region under compressive actions. For the quality assurance of the friction stir welded region, non-destructive test (NDT) methods can be used to find any defects.

• The friction stir lap-weld between plate sheet and extruded stiffener is considered to be a promising welding method to replace the fusion fillet-weld procedure in construction of aluminum structures. The post-collapse delamination is of no major concern for the friction stir lap-welds because it can still maintain the water tightness of the stiffened plate structure, although the pre- or post-collapse delamination is of great concern for the friction stir butt-welds because it can assure no longer the water tightness of the stiffened panel. However, since the pre-collapse delamination reduces the ultimate strength significantly, further study is needed to verify the mechanical property of the friction stir lap-weld and its parameter which will affect the mechanical property and delamination between base plate and stiffener such as width and depth of molten thin-layer, molten temperature, rotating and forwarding speeds, and possible quick cooling, etc.

• It is reconfirmed that nonlinear finite element method computations depend significantly on the structural modeling techniques applied.
Acknowledgements

The present study was undertaken at the Lloyd’s Register Educational Trust (LRET) Research Centre of Excellence, Pusan National University, Korea. Thanks are due to graduate students at the Ship and Offshore Structural Mechanics Laboratory of the Pusan National University for their efforts regarding buckling collapse tests and nonlinear finite element method computations.

In addition, this author would like to thank Ship Structure Committee (SSC) for its financial and technical assistance. SSC is an inter-agency organization chaired by US Coast Guard with the goal of eliminating marine structural failures. Member agencies consist of American Bureau of Shipping (ABS), Defence Research Directorate Canada (DRDC), US Maritime Administration (MARAD), Military Sealift Command (MSC), Naval Sea Systems Command (NAVSEA), Transport Canada, Society of Naval Architects and Marine Engineers (SNAME) and the US Coast Guard (USCG). Without the SSC support, it certainly would not have been able to complete this project. Special thanks are due to the members of SSC Project Technical Committee chaired by Mr. Chao Lin, for their valuable comments and advices.
Notation

\( a \) = panel length between transverse frames
\( A_i \) = area of the \((i)\)th cross-section in the stiffened panel
\( b \) = breadth of the plating between longitudinal stiffeners
\( b_{HAZ} \) = half-breadth of the softened zone
\( b_i \) = breadth of tensile residual stress block
\( B \) = breadth of the entire stiffened panel
\( E \) = elastic modulus (Young’s modulus)
\( P_p \) = fully plastic axial force without consideration of buckling = \( \sum_i A_i \sigma_{Yi} \)
\( P_u \) = ultimate axial compressive force
\( t \) = plate thickness
\( w_{oc} \) = maximum column-type initial distortion of stiffener
\( w_{opl} \) = maximum initial deflection of plating
\( w_{os} \) = maximum sideways initial distortion of stiffener
\( \beta \) = plate slenderness ratio
\( \lambda \) = column slenderness ratio for either a single stiffener with attached plating or the entire stiffened panel
\( \sigma_{rcx} \) = compressive residual stress in the x direction
\( \sigma_{rtx} \) = tensile residual stress in the x direction
\( \sigma_x \) = applied compressive stress in the x direction
\( \sigma_{su} \) = ultimate compressive strength of structure
\( \sigma_T \) = ultimate tensile strength of material
\( \sigma_Y \) = yield strength of material in general
\( \sigma_{Yi} \) = yield strength of material in the \((i)\)th cross-section
\( \sigma_{Yeq} \) = equivalent yield strength of material in general = \( \sum_i A_i \sigma_{Yi} / \sum_i A_i \)
\( \sigma_{YHAZ} \) = reduced yield strength in the softened zone

Abbreviation

FEA = finite element analysis
FSW = friction stir welding
GMAW = gas metal arc welding, which is also termed metal inert gas (MIG) welding
HAZ = heat-affected zone
SSC = The Ship Structure Committee
TMAZ = thermo-mechanically affected zone
ULS = ultimate limit states
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Chapter 1 Introduction

1.1 Objectives
The primary objectives of the present study are as follows.

• To develop a mechanical buckling collapse test database of full-scale prototypes of 5000’s and 6000’s series aluminum stiffened plate structures fabricated by the friction stir-welding (FSW) procedure.
• To provide a comparison of these structures with similar aluminum plate panels fabricated by the fusion welding procedure and to note any trends or benefits associated with either procedure.

1.2 Background
The use of high-strength aluminum alloys in the shipbuilding industry provides many benefits, but also presents many challenges (Collette 2005, Sielski 2007, 2008). The benefits of using aluminum rather than steel include its lighter weight, which helps increase cargo capacity and/or reduce power requirements, excellent corrosion resistance and low maintenance. The challenges include reduced stiffness, which results in greater sensitivity to deformation, buckling and plastic collapse, and the need for different welding practices.

The aforementioned benefits are now well-recognized, particularly for the design and construction of war ships, littoral surface craft and combat ships, and fast passenger ships, particularly as such ocean-going vessels are becoming increasingly large in size.

The increasing size of these vessels, however, has resulted in a number of design challenges. Aluminum alloys are less stiff than mild steel, and no refined ultimate limit state (ULS) design methods that involve local and overall ULS assessments exist, unlike the case with steel structures for which the necessary information is plentiful. The use of ULS design methods (ISO 2007), in addition to more conventional structural design standards, will help in the design and construction of very large, high-speed, ocean-going aluminum vessel structures (Paik et al. 2005).

The SSC-451 report (Paik et al. 2008b) presented an extensive investigation of the collapse characteristics of the aluminum stiffened plate structures used for marine applications carried out via mechanical testing and nonlinear finite element method computations. The features of the initial imperfections found were examined together with a statistical database of the fabrication-related initial imperfections in fusion-welded aluminum stiffened plate structures, because such imperfections significantly affect ULS behavior. This database and the insights presented in the SSC-451 report are very useful in the design and construction of high-speed, fusion-welded aluminum ocean-going vessel structures.

Various welding methods are used today to fabricate aluminum ship structures, namely, gas metal arc welding (GMAW), laser welding and FSW. The SSC-451 report focuses on the GMAW technique for the construction of its test structures, as it is currently one of the most popular methods of welding in aluminum ship construction.

FSW, however, has also been recognized as a very attractive joining method for aluminum structures because of its many superior features, such as excellent joint
performance, small degree of initial imperfections, low level of energy consumption and lack of harmful emissions (Dawes & Thomas 1995). FSW technology has been applied successfully to various aluminum structures, such as railcars, automobiles and bridges (Thomas & Nicholas 1997, Midling et al. 1998, Sanderson et al. 2000).

However, these applications are mostly suitable for 6000’s series aluminum alloys, and more R&D efforts are required to extend them to such structures as fast ships and spherical liquefied natural gas (LNG) cargo tanks made of 5000’s series aluminum alloys, which are the major alloys used for marine applications (Kalle 2000, Przydatek 2000).

It was once considered to be too difficult to apply FSW to 5000’s series aluminum alloys due to their poor fluidity at welding temperatures. Recently, however, FSW machines have been developed to deal with the fabrication of products made with these alloys, and they are able to produce good-quality welds of up to 25 mm in thickness. Also, it has been confirmed in the literature that the fatigue strength characteristics of 5000’s series aluminum structural details fabricated by FSW are good enough when compared to fillet-welded details (Nicholas 1998).

However, there is no mechanical test database in the literature on the buckling collapse strength of 5000’s and 6000’s series aluminum structures fabricated by FSW. As ultimate buckling strength is today a primary design basis for both aluminum and steel ship structures, the development of a related mechanical buckling collapse test database is a matter of urgency.

Although the SSC-451 report presents a mechanical buckling collapse test database for fusion-welded aluminum plate structures, the results of a comparison of this database with the FSW procedures in terms of the trends and benefits associated with their buckling collapse strength characteristics and fabrication-related initial imperfections would be very useful in the design and construction of large ocean-going aluminum ship structures.

1.3 Requirements
1.3.1 Scope
- Investigate FSW fabrication-related initial imperfections.
- Perform buckling collapse tests on full-scale prototypes of 5000’s and 6000’s series aluminum plate structures fabricated by FSW.
- Perform non-linear elastic-plastic large deformation finite element method computations on the test structures.
- Perform comparisons between fusion welds and FSW in terms of their fabrication-related initial imperfections and buckling collapse strength characteristics.

1.3.2 Tasks
- Review the state-of-the-art of FSW technologies.
- Design and fabricate aluminum stiffened plate structures for buckling collapse testing.
- Identify the chemical composition and mechanical properties of the materials used for the test structures.
- Measure the fabrication-related initial imperfections of these test structures and compare them with the database of SSC-451 in terms of FSW versus fusion welds.
• Perform buckling collapse testing on the test structures under axial compressive conditions until and after the ultimate strength is reached.
• Perform nonlinear finite element method analyses to compute the ultimate strength behavior of the test structures and compare them with the experimental results.
• Discuss the trends and benefits associated with FSW and fusion welds in terms of their ultimate compressive strength performance.

1.4 Literature Survey

More than 210 articles and papers in the area of FSW technologies published or presented as of January 2009 have been collected, although most are not directly related to the aims and scope of the present project. Only one Ship Structure Committee (SSC) project has previously been undertaken in this area, which produced the SSC-447 report (Kramer 2007), but its focus was on fatigue strength performance.

The following provides a summary of the literature survey, with a focus on the aims and scope of the present project and related findings.

FSW technology was developed in 1991 by the Welding Institute in the U.K. (Thomas et al. 1991, 1995). FSW is a solid-state joining process that is particularly suitable for aluminum alloys that often face problems with fusion welds, such as cracks, porosity, distortion or softening. This technology has been recognized to have many advantages for the construction of aluminum structures, as it is a low-cost welding process. Aluminum alloys tend to show cracks and porosity after fusion welding, but FSW minimizes such problems because of the low input of total heat. The use of protective gases, e.g., for toxic shielding, may be unnecessary.

There have, of course, been useful studies that characterize the mechanical properties of FSW aluminum alloys (e.g., Rhodes et al. 1997, Hagstrom & Sandstrom 1998, Hashimoto et al. 1998, Mahoney et al. 1998, Biallas et al. 1999) and compare the properties of base and welded metals. A large number of studies on the strength performance of FSW aluminum structural details under fatigue conditions have also been undertaken (e.g., Kamioka & Okubo 2005, Kramer 2007).

The applications of FSW technologies for shipbuilding were studied by Thomas (1998) and Thomas et al. (2002, 2005), among others. Colligan (2004) presented FSW applications for ship design and construction, together with a discussion of the use of FSW technology in the United States, and indicated that it is capable of reducing construction costs and welding distortion and improving durability in comparison with fusion welding.

Peel et al. (2003) investigated the mechanical properties and residual stresses of a FSW aluminum 5083 test specimen, and concluded that these properties are governed by the thermal input rather than by the mechanical deformation caused by the FSW tool.

Several studies have also identified the residual stress characteristics in FSW aluminum structures. For example, Bang et al. (2002) predicted the residual stresses of FSW 6061 aluminum alloy using the thermal-elastic-plastic finite element method; Staron et al. (2004) measured the residual stresses in FSW aluminum 2024 sheets; and Fratini & Zuccarello (2006) presented an analysis of the through-thickness residual stresses in aluminum FSW butt joints.

Prime et al. (2006) measured the residual stresses in thick plates (25.4 mm thick)
of dissimilar aluminum alloys, 7050-T7451 and 2024-T351, that had been butt-joined by FSW. The maximum residual stress was found to be only 43 MPa, whereas the residual stress distribution was quite similar to that in fusion welds, thus indicating that the tensile residual stress develops in the heat-affected zone outside of the weld.

Khandkar et al. (2006) studied the residual stress of such FSW metals as aluminum 2024, aluminum 6061 and stainless steel 304L using a sequentially coupled finite element model with the FSW process. Murphy et al. (2007) performed a very similar study to the one presented here in terms of its aims and scope, including weld-induced initial imperfection measurements, buckling collapse testing and nonlinear finite element computations, although the purpose of their study was to examine aerospace structures made of aluminum 2024-T3 sheet with Z-section stiffeners of aluminum 7075-T7651 extrusions. They used the FSW method to construct three stiffened 332.70-mm × 575-mm panel test structures with 152.4 mm spacing for the three longitudinal stiffeners. The plate (skin) thickness was very thin (1.2 mm thick). Murphy et al. (2007) measured the initial distortions and residual stresses of these structures, as well as the breadth of the heat-affected zone. They carried out buckling collapse tests for the three stiffened panels and compared their experimental results with nonlinear finite element solutions.

Other researchers have investigated the effects of the process parameters on the residual stresses of FSW aluminum alloys (Lombard et al. 2009, Zhang & Zhang 2009a, 2009b), as well as the effects of the welding parameters on the mechanical properties of dissimilar aluminum alloy joints produced by FSW (Cavaliere et al. 2009). The rotating and forwarding speeds were considered as the parameters of influence in these studies.

As we have seen, a large number of studies that deal with micro-structural and fatigue issues in FSW aluminum structures have been undertaken. However, there is a lack of studies on the characterization of FSW-induced initial imperfections and the buckling collapse strength performance of aluminum structures for marine applications. Therefore, research and development are required to identify the characteristics of the ultimate strength performance of FSW aluminum structures.

1.5 Contents of the Report

This report comprises eight chapters and appendix. Chapter 1 addresses the aims and scope of the study together with a literature survey. Chapter 2 presents an outline of the FSW technology in terms of its advantages and limitations. Chapter 3 describes the design and construction of the test structures and documents the chemical composition and mechanical properties of the materials used for these structures, as well as the fabrication methods adopted. Chapter 4 presents the measurements of the weld-induced initial imperfections in the test structures, and a comparison is made between fusion welds and FSW in terms of these imperfections. Chapter 5 summarizes the results of the buckling collapse tests on the test structures, and Chapter 6 presents the nonlinear finite element method computations for these structures by a comparison with the experimental results. Chapter 7 discusses the benefits and trends associated with FSW and fusion welds in terms of their ultimate compressive strength performance, and finally Chapter 8 presents concluding remarks. Appendix presents the mechanical properties of aluminum alloys which experienced
buckling collapse.

It is hoped and believed that the results of the present project will be very useful in the design and construction of aluminum ship structures using FSW technologies in association with ULS-based approaches.
Chapter 2 Fusion Welds versus Friction Stir Welds for Aluminum Structures: An Overview

2.1 Classification of Welding Processes

Although a large number of methods for joining metals are available today, they may be classified into the following five basic categories (Masubuchi 1980).

- Fusion welding, e.g., gas metal arc welding (GMAW), gas tungsten arc welding (GTAW)
- Electrical-resistance welding
- Solid-phase welding, e.g., friction stir welding (FSW)
- Liquid-solid phase joining
- Adhesive bonding

In the fusion-welding process, the parts to be joined are heated until they melt together, and pressure is not a requisite. Examples of fusion welding include gas welding, arc welding, electron-beam welding and laser welding. Fusion welds that use inert gases, such as gas metal arc welding (GMAW) or gas tungsten arc welding (GTAW), are often applied to join aluminum structures.

In the electrical-resistance welding process, heating is first involved via the passage of an electric current through the parts to be welded, followed by the application of pressure. Examples of electrical-resistance welding include spot welding, upset welding and percussion welding.

The solid-phase welding process is similar to that of electrical-resistance welding in terms of the application of pressure, but the metals to be joined are not melted, except for the very thin layers near the surfaces to be joined. Examples of solid-phase welding include friction welding, forge welding and pressure welding. In this regard, FSW can be considered a type of solid-phase welding.

In the liquid-solid phase joining process, the parts to be joined are heated to a temperature lower than their melting points, and a dissimilar molten metal is then added to form a solid joint upon cooling. Examples of liquid-solid phase joining include brazing and soldering.

Finally, the adhesive bonding process makes use of the molecular attraction exerted between the surface to be bonded and the adhesive. Examples of such bonding include animal and vegetable glues, cements, asphaltums and various plastics (e.g., epoxy).

It should be noted that the processes of the first three categories are termed ‘welding’, whereas those of the latter two are often termed ‘joining’.

2.2 Fusion Welds

Although various fusion-weld technologies are used in the fabrication of large-sized metal structures, inert gas-oriented fusion welds are today the most popular in the construction of aluminum structures.

Fusion-weld technology provides a cost-effective tool in terms of speed, accuracy and weld-joint performance in the fabrication of such structures. However, a number
of issues arise from the use of fusion welds in aluminum alloys for marine applications, such as 5000’s or 6000’s series alloys, including fabrication-related initial imperfections and a subsequent reduction in strength performance. Collette (2007) presented an excellent review of the impact of fusion welds in association with the ultimate strength performance of aluminum structures. Figure 2.1 presents a photo of the GMAW-based fusion-welding process.

2.3 Friction Stir Welds
2.3.1 Principles of the Process
FSW is a type of solid-phase welding, as noted in Section 2.1. This technology was developed by the Welding Institute in the U.K. in 1991.

Figure 2.2 illustrates a schematic of the FSW process. The metal plates to be joined are clamped onto a rigid backing body. This set-up is necessary to avoid any movement of the target plates during the welding process, such as movement in the longitudinal, transverse and lateral directions during pressing and plunging. The tip of the FSW tool, with a specially designed and profiled probe called a pin and shoulder, as shown in Figure 2.3, is rotated under sufficient downward force at high speed, and then moves slowly along the joint line.

The FSW process may be classified into the following five steps (see Figure 2.4).
• Step 1: Set-up the target plates to be joined, which are clamped onto a rigid backing body.
• Step 2: Equip the machine with the FSW tool (pin) and place it over the starting point of the joint.
• Step 3: Plunge the rotating FSW tool under sufficient downward force.
• Step 4: After touchdown, heat and plasticize the local material at the starting point of the joint.
• Step 5: Move the FSW tool along the joint line, thus transporting the plasticized material around the rotating pin.

The pin size (e.g., diameter and length), shoulder width, and rotating and forwarding speed of the FSW tool are chosen based on the properties of the target plates to be joined, such as plate thickness, material type and others. Figure 2.5 presents a photo of the FSW process.

Figure 2.2 Schematic of the FSW process (Thomas et al. 1991)
Figure 2.3 Pin and shoulder of the FSW tool (Thomas et al. 1991)

Figure 2.4 Steps of the FSW process (Thomas et al. 1991)
2.3.2 Advantages and Limitations

Compared to the fusion-welding process, that for FSW is considered to be more attractive, although there are some limitations to its application. Kramer (2007) summarized the advantages and limitations of friction stir welds, as discussed below.

The advantages of the FSW process primarily result from the fact that it works in the solid state at a low temperature that is below the melting point of the materials to be joined. This is in contrast to the fusion-welding process. Thus, the level of fabrication related-initial imperfections in structures built by FSW should subsequently be slight and/or less severe than those produced by fusion welds.

The limitations of FSW applications may include the following:

- The pins of the FSW tool are consumable, and their size (diameter and length) differs depending on the properties of the plates to be joined.
- The position of welding is limited due to the orientation of the FSW machine, including the tool. Fillet welding is not relevant because inclining the target plates and/or the FSW machine along the intersections to be joined between the plate and extrusion is not straightforward.
- Butt-joining is relevant, but there must be no obstacles around the FSW machine that can disturb the rotating and forwarding of the tool.
- Lap-joining is relevant, but the pin size must be carefully chosen.
- A keyhole is formed at the end of each weld, as shown in Figure 2.6.
• The speed of FSW is usually slower than that of fusion welding.
• A weld nugget may form at the center of the weld.

![Figure 2.6 Keyhole at the end of the friction stir weld](image)

The mechanical property and strength performance in the friction stir welded region is affected by various parameters such as width and depth of molten thin layer, molten temperature, rotating and forwarding speeds, and possible quick cooling, etc. The quality assurance of the friction stir welded region can be performed by non-destructive test (NDT) methods to find any defects.

### 2.3.3 The Softened Zone

In contrast to fusion welding, in which three distinct regions, i.e., the base (parent or unaffected) material, the weld metal region, and the heat-affected zone (HAZ), typically appear, FSW may produce more complicated micro-structural phenomena, thus exhibiting four regions: A - the unaffected material, B - the heat-affected zone (HAZ), C - the thermo-mechanically affected zone (TMAZ) and D - the weld nugget, as shown in Figure 2.7 (Kramer 2007).

The parent material region is unaffected by heat and/or mechanical deformation. The mechanical properties of this material are supposed to be the same as those of virgin material.

The HAZ of friction stir welds appear to be similar to fusion welds, but have lower peak temperatures. The material in this region undergoes a thermal process cycle during welding, and, subsequently, in the case of aluminum alloys, the mechanical properties of this material are usually softened by micro-structural phenomena in the HAZ, although plasticity may not take place.

The TMAZ typically appears together with plastic deformation in the region in which the FSW tool is plunged and rotated. The TMAZ is often further categorized into two sub-zones, namely, the plastically deformed zone without recrystallization and
the recrystallized (weld-nugget) zone. In the case of aluminum alloys, the mechanical properties of material in the TMAZ may differ from those in the HAZ as well as those of the base material.

For the sake of convenience when evaluating ultimate strength performance, however, both the HAZ and TMAZ are often dealt with as a whole in the form of the softened zone, but with the breadth of this zone being equivalent to approximately two times the width of the FSW tool shoulder.

![Figure 2.7 Schematic of the TMAZ and HAZ associated with FSW (Kramer 2007)](image)

A: Unaffected material  
B: Heat-affected zone (HAZ)  
C: Thermo-mechanically affected zone (TMAZ)  
D: Weld nugget (Part of thermo-mechanically affected zone)

Figure 2.7 Schematic of the TMAZ and HAZ associated with FSW (Kramer 2007)
3.1 Selection of Materials

3.1.1 Combinations for Plate and Extrusions

Although 5000’s and 6000’s series aluminum alloys are typically appropriate for marine applications, the plate part is usually fabricated from 5000’s series alloys and the extrusions from 5000’s or 6000’s series alloys.

Considering this trend and the limitations of material procurement, the following combinations of aluminum alloys for the plate and extrusions were chosen for the present study.

- 5083-H112 alloy for the plate and 6082-T6 alloy for the extrusions
- 5083-H112 alloy for the plate and 5083-H112 alloy for the extrusions
- 5383-H116 alloy for the plate and 5083-H112 alloy for the extrusions

The SSC-451 database (Paik et al. 2008b) is used in the comparison stage for fusion welds versus friction stir welds in conjunction with ultimate strength performance. The material combinations for the test structures in SSC-451 are as follows.

- 5083-H116 alloy for the plate and 5383-H112 alloy for the extrusions
- 5083-H116 alloy for the plate and 6082-T6 alloy for the extrusions
- 5383-H116 alloy for the plate and 5383-H112 alloy for the extrusions

The manufacturers (of suppliers) of the aluminum alloys procured for the present study and the year of their production are as follows.

- 5083-H112 alloy for the plate - Alcoa Korea, 2008
- 5083-H112 alloy for the extrusions - Alcoa Korea, 2008
- 5083-H116 alloy for the plate - Alcan France, 2006
- 5383-H112 alloy for the extrusions - Alcan France, 2006
- 5383-H116 alloy for the plate - Alcan France, 2006
- 6082-T6 alloy for the extrusions - Alcoa Korea, 2008

3.1.2 Chemical Composition

Table 3.1 lists the chemical composition of all of the alloys investigated in the present study, which is equivalent to that of the typical aluminum alloys used in marine applications. It should be noted that the chemical composition of rolled plates differs from that of extrusions.

3.1.3 Mechanical Properties

3.1.3(a) Base Material

Tensile coupon tests were carried out to identify the mechanical properties of the base material and the material in the welded parts. Figure 3.1 shows the dimensions
of the tensile coupon test specimen in conjunction with the American Society for Testing and Materials (ASTM) standards.

Three types of specimens with plate thicknesses of 6 mm were cut out of the plate part, namely, in the longitudinal (rolled), transverse and diagonal directions, whereas only one type of specimen with a plate thickness of 4 mm or 6 mm was taken from the extrusions in the length direction.

### Table 3.1 Chemical composition (wt. %) of aluminum alloys used in the present study

<table>
<thead>
<tr>
<th>Alloy &amp; Temper</th>
<th>Si (%)</th>
<th>Fe (%)</th>
<th>Cu (%)</th>
<th>Mn (%)</th>
<th>Mg (%)</th>
<th>Cr (%)</th>
<th>Zn (%)</th>
<th>Ti (%)</th>
<th>Zr (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5083-H112 (R)¹</td>
<td>0.12</td>
<td>0.29</td>
<td>0.014</td>
<td>0.65</td>
<td>4.55</td>
<td>0.088</td>
<td>0.006</td>
<td>0.031</td>
<td>0.0</td>
</tr>
<tr>
<td>5083-H112 (E)¹</td>
<td>0.14</td>
<td>0.12</td>
<td>0.010</td>
<td>0.64</td>
<td>4.56</td>
<td>0.080</td>
<td>0.010</td>
<td>0.030</td>
<td>0.0</td>
</tr>
<tr>
<td>5083-H116 (R)²</td>
<td>Max. 0.40</td>
<td>Max. 0.40</td>
<td>Max. 0.10</td>
<td>0.4</td>
<td>-1.0</td>
<td>4.0</td>
<td>-4.9</td>
<td>0.05</td>
<td>Max. 0.25</td>
</tr>
<tr>
<td>5383-H112 (E)²</td>
<td>Max. 0.25</td>
<td>Max. 0.25</td>
<td>Max. 0.20</td>
<td>0.7</td>
<td>-1.0</td>
<td>4.0</td>
<td>-5.2</td>
<td>Max. 0.25</td>
<td>Max. 0.40</td>
</tr>
<tr>
<td>5383-H116 (R)¹</td>
<td>0.091</td>
<td>0.24</td>
<td>0.077</td>
<td>0.82</td>
<td>4.97</td>
<td>0.088</td>
<td>0.11</td>
<td>0.011</td>
<td>0.002</td>
</tr>
<tr>
<td>Al6082-T6 (E)¹</td>
<td>1.22</td>
<td>0.22</td>
<td>0.07</td>
<td>0.69</td>
<td>1.05</td>
<td>0.19</td>
<td>0.01</td>
<td>0.03</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Note: ¹) Tested by Alcoa Korea, ²) Provided by Alcan France, (E) = extruded, (R) = rolled.

---

![Figure 3.1(a) Specimen of tensile coupon tests for the mechanical property characterization of the base material - rolled plate part](image)

![Figure 3.1(b) Specimen of tensile coupon tests for the mechanical property characterization of the base material - extruded web part](image)
It should be noted that the mechanical properties of rolled alloys may differ from those of extruded alloys because their production process is different. Therefore, the specimens corresponding to the plate part and extrusions need to be prepared for testing. For the latter, only the material in the web part was tested in the present study.

Figure 3.2 shows the relationships between the engineering stress and the engineering strain, as obtained from the tensile coupon tests, where some materials were tested with multiple test specimens cut out in the same direction.

Table 3.2 provides a summary of the mechanical properties of the base materials, which were also obtained from these tests. Table 3.3 lists the minimum requirements of the mechanical properties of the base materials, as specified by the classification societies (ABS 2006, LR 2008).
Figure 3.2(b) The stress versus strain curves for the aluminum base material - 5083-H112 (extruded) - obtained from the tensile coupon tests

Figure 3.2(c) The stress versus strain curves for the aluminum base material - 5083-H116 (rolled) - obtained from the tensile coupon tests
Figure 3.2(d) The stress versus strain curves for the aluminum base material - 5383-H112 (extruded) - obtained from the tensile coupon tests

Figure 3.2(e) The stress versus strain curves for the aluminum base material - 5383-H116 (rolled) - obtained from the tensile coupon tests
Figure 3.2(f) The stress versus strain curves for the aluminum base material - 6082-T6 (extruded) - obtained from the tensile coupon tests
Table 3.2 Summary of the mechanical properties of the aluminum alloys (base material), obtained from the tensile coupon tests

<table>
<thead>
<tr>
<th>Material</th>
<th>Specimen</th>
<th>$E$ (N/mm²)</th>
<th>$\sigma_Y$ (N/mm²)</th>
<th>$\sigma_T$ (N/mm²)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5083-H112 (R) (t = 6mm)</td>
<td>L-type</td>
<td>69420</td>
<td>164</td>
<td>310</td>
<td>32.28</td>
</tr>
<tr>
<td></td>
<td>T-type</td>
<td>70700</td>
<td>167</td>
<td>308</td>
<td>33.59</td>
</tr>
<tr>
<td></td>
<td>D-type</td>
<td>69434</td>
<td>162</td>
<td>305</td>
<td>33.40</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>69856.8</td>
<td>167.2</td>
<td>307.67</td>
<td>33.09</td>
</tr>
<tr>
<td>5083-H112 (E) (t = 6mm)</td>
<td>L-type 1</td>
<td>70231</td>
<td>132</td>
<td>258</td>
<td>23.58</td>
</tr>
<tr>
<td></td>
<td>L-type 2</td>
<td>70149</td>
<td>148</td>
<td>271</td>
<td>19.98</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>70190</td>
<td>140</td>
<td>264.5</td>
<td>21.78</td>
</tr>
<tr>
<td>5083-H116 (R) (t = 6mm)</td>
<td>T-type</td>
<td>73129</td>
<td>239</td>
<td>353</td>
<td>21.4</td>
</tr>
<tr>
<td>5383-H112 (E) (t = 6mm)</td>
<td>L-type 1</td>
<td>69911</td>
<td>159</td>
<td>282</td>
<td>18.37</td>
</tr>
<tr>
<td></td>
<td>L-type 2</td>
<td>70149</td>
<td>148</td>
<td>282</td>
<td>18.85</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>70030</td>
<td>153.5</td>
<td>282</td>
<td>18.61</td>
</tr>
<tr>
<td>5383-H116 (R) (t = 6mm)</td>
<td>L-type 1</td>
<td>70751</td>
<td>194</td>
<td>348</td>
<td>26.72</td>
</tr>
<tr>
<td></td>
<td>L-type 2</td>
<td>70427</td>
<td>193</td>
<td>326</td>
<td>24.73</td>
</tr>
<tr>
<td></td>
<td>T-type</td>
<td>69887</td>
<td>215</td>
<td>352</td>
<td>25.64</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>70355.3</td>
<td>207.9</td>
<td>342</td>
<td>25.85</td>
</tr>
<tr>
<td>6082-T6 (E) (t = 4mm)</td>
<td>L-type</td>
<td>68359</td>
<td>304</td>
<td>306</td>
<td>11.53</td>
</tr>
<tr>
<td>6082-T6 (E) (t = 6mm)</td>
<td>L-type</td>
<td>68723</td>
<td>343</td>
<td>359</td>
<td>12.93</td>
</tr>
</tbody>
</table>

Note: (R) = rolled; (E) = extruded; $E$ = elastic modulus; $\sigma_Y$ = yield strength; $\sigma_T$ = ultimate tensile strength; L-type = Longitudinal; T-Type = Transverse; D-type = Diagonal.
Table 3.3 Minimum requirements for the mechanical properties of aluminum alloys - base material (ABS 2006, LR 2008)

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>$\sigma_Y$ (N/mm$^2$)</th>
<th>$\sigma_T$ (N/mm$^2$)</th>
<th>Elongation in 50 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5083-H112 (R)</td>
<td>6.5-38.0</td>
<td>124.5</td>
<td>275.4</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>38.1-76.5</td>
<td>117.6</td>
<td>268.5</td>
<td>12</td>
</tr>
<tr>
<td>5083-H112 (E)</td>
<td>-</td>
<td>109.8</td>
<td>268.5</td>
<td>12</td>
</tr>
<tr>
<td>5083-H116 (R)</td>
<td>1.6-38.0</td>
<td>213.6</td>
<td>302.8</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>38.1-76.5</td>
<td>199.9</td>
<td>282.8</td>
<td>10</td>
</tr>
<tr>
<td>5083-H321 (R)</td>
<td>1.6-38.0</td>
<td>213.6</td>
<td>302.8</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>38.1-76.5</td>
<td>199.9</td>
<td>282.8</td>
<td>10</td>
</tr>
<tr>
<td>5383-H111 (R)</td>
<td>3.0-5.0</td>
<td>142.1</td>
<td>284.2</td>
<td>17</td>
</tr>
<tr>
<td>5383-H111 (E)</td>
<td>-</td>
<td>145.0</td>
<td>290.1</td>
<td>17</td>
</tr>
<tr>
<td>5383-H112 (E)</td>
<td>-</td>
<td>190.1</td>
<td>309.7</td>
<td>13</td>
</tr>
<tr>
<td>5383-H116 (R)</td>
<td>3.0-5.0</td>
<td>215.6</td>
<td>298.9</td>
<td>10</td>
</tr>
<tr>
<td>5383-H321 (R)</td>
<td>3.0-5.0</td>
<td>215.6</td>
<td>298.9</td>
<td>10</td>
</tr>
</tbody>
</table>

Note: (R) = rolled; (E) = extruded; $E$ = elastic modulus; $\sigma_Y$ = yield strength; $\sigma_T$ = ultimate tensile strength.

3.1.3(b) Welded Material

To characterize the mechanical properties of the welded aluminum alloys, butt-joined specimens with a plate thickness of 6 mm were prepared via both the fusion-welding and friction stir welding (FSW) processes, as shown in Figure 3.3. The condition of each weld is as follows.

- Fusion weld: Filler metal - 5183 aluminum alloy, diameter of filler wire - 1.2 mm, shield gas - 100% Ar, inert gas, welding speed - 450 mm/min, electricity - 183 A and 21 V, torch angle - 50 degrees, welding progress angle - 80 degrees.
- Friction stir weld: Rotating speed of FSW tool - 1500 RPM, forwarding speed of FSW tool - 4 mm/s, weld temperature - approximately 370ºC, FSW tool size - $d_1 = 4$mm, $d_2 = 5$ mm, $d_3 = 15$ mm, $h = 5.4$mm, with the nomenclature in Figure 3.4.

The tensile coupon test specimens for the butt-welds were prepared for the combination of dissimilar alloys as well as for the identical alloys as follows.

- 5083-H112 + 5083-H112
• 5383-H116 + 5383-H116
• 5083-H112 + 5383-H116

Figure 3.5 shows the stress versus strain curves of the butt-welded aluminum alloys, as obtained from the tensile coupon tests. Multiple test specimens with the same weld condition were prepared. It is observed that a somewhat significant deviation exists in elongation of friction stir-welded region. A comparison of these curves for welded aluminum alloys fabricated by fusion welding and by FSW is also shown in this figure. It is found that the mechanical properties of aluminum material fabricated by friction stir welding are equivalent to or can be better than those by fusion welding.

Table 3.4 summarizes the mechanical properties of the butt-welded aluminum alloys, as obtained from the tensile coupon tests. Table 3.5 presents the minimum yield strength requirements for fusion-welded aluminum alloys, which are similar to those of the present study.

It is noted that the tensile coupon tests were performed for butt welds only in the present study, and thus further study is needed to verify the tensile properties of the friction stir lap-welded material. A microscopic examination of the friction stir lap-welded material is recommended to find any defects associated with the width and depth of the molten metal thin layer which potentially cause delamination in pre- or post-collapse range of the structure under compressive actions involving buckling or crushing.
Figure 3.5(a) The stress versus strain curves for fusion-welded aluminum material - 5083-H112 plus 5083-H112 - obtained from the present tensile coupon tests

Figure 3.5(b) The stress versus strain curves for FSW aluminum material - 5083-H112 plus 5083-H112 - obtained from the present tensile coupon tests
Figure 3.5(c) The stress versus strain curves for fusion welded aluminum material - 5083-H112 plus 5383-H116 - obtained from the tensile coupon tests

Figure 3.5(d) The stress versus strain curves for FSW aluminum material - 5083-H112 plus 5383-H116 - obtained from the tensile coupon tests
Figure 3.5(e) The stress versus strain curves for fusion-welded aluminum material – 5383-H116 plus 5383-H116 – obtained from the present tensile coupon tests

Figure 3.5(f) The stress versus strain curves for FSW aluminum material – 5383-H116 plus 5383-H116 – obtained from the present tensile coupon tests
Figure 3.5(g) Comparison of the stress versus strain curves for welded aluminum material fabricated by fusion welding and FSW - 5083-H112 plus 5083-H112 - obtained from the tensile coupon tests

Figure 3.5(h) Comparison of the stress versus strain curves for welded aluminum material fabricated by fusion welding and FSW - 5383-H116 plus 5383-H116 - obtained from the tensile coupon tests
Figure 3.5(i) Comparison of the stress versus strain curves for welded aluminum material fabricated by fusion welding and FSW - 5083-H112 plus 5383-H116 - obtained from the tensile coupon tests
Table 3.4 Summary of the mechanical properties of welded aluminum alloys, obtained from the tensile coupon tests

<table>
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<tr>
<th>Material</th>
<th>Weld specimen</th>
<th>$E$ (N/mm$^2$)</th>
<th>$\sigma_Y$ (N/mm$^2$)</th>
<th>$\sigma_T$ (N/mm$^2$)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5083-H112 + 5083-H112</td>
<td>GMAW 1</td>
<td>71685</td>
<td>125</td>
<td>176</td>
<td>2.86</td>
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<tr>
<td></td>
<td>GMAW 2</td>
<td>68753</td>
<td>135</td>
<td>191</td>
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</tr>
<tr>
<td></td>
<td>Average</td>
<td>70219</td>
<td>130</td>
<td>183.5</td>
<td>3.16</td>
</tr>
<tr>
<td>5083-H112 + 5083-H112</td>
<td>FSW 1</td>
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<td>137</td>
<td>236</td>
<td>6.58</td>
</tr>
<tr>
<td></td>
<td>FSW 2</td>
<td>70699</td>
<td>134</td>
<td>263</td>
<td>12.32</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>69938.5</td>
<td>135.5</td>
<td>249.5</td>
<td>9.45</td>
</tr>
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<td>5083-H112 + 5383-H116</td>
<td>GMAW 1</td>
<td>70733</td>
<td>124</td>
<td>224</td>
<td>5.73</td>
</tr>
<tr>
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<td>214</td>
<td>4.86</td>
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<td>FSW 1</td>
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<td>FSW 2</td>
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<td>137</td>
<td>269</td>
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<td>Average</td>
<td>70076.5</td>
<td>137</td>
<td>270</td>
<td>13.79</td>
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<td>262</td>
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Note: $E$ = elastic modulus; $\sigma_Y$ = yield strength; $\sigma_T$ = ultimate tensile strength.
Table 3.5 Minimum yield strength requirements for fusion-welded aluminum alloys, as specified by various regulations (MPa)

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<td>110</td>
<td>145</td>
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<td>115</td>
<td>165</td>
<td>125</td>
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<tr>
<td>5383-H111(E)</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>145</td>
</tr>
<tr>
<td>5383-H116(R)</td>
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<td>140</td>
<td>-</td>
<td>-</td>
<td>145</td>
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</tbody>
</table>

Note: (E) = extruded; (R) = rolled; ABS = American Bureau of Shipping; DNV = Det Norske Veritas (Yield strength $\sigma_1$ is determined from the values of $f_1$ published by the equation $\sigma_1 = f_1 \times 240 / 1.1$); AA = Aluminum Association; AWS = American Welding Society.

3.2 Structural Dimensions and Profiles

3.2.1 Panel Dimensions

The principal dimensions of the test structures used in the present project were basically the same as those in SSC-451, although some small differences arose because of the different fabrication methods. Figure 3.6 shows a schematic of the dimensions of the test structures with the relevant nomenclature. The panel had a total of four longitudinal stiffeners or extrusions, and the transverse frame was attached at each end of the panel to be used for clamping with the test facility before the buckling collapse testing.

Tables 3.6(a) and 3.6(b) list the details of the principal dimensions of the structures tested in the present study and those in SSC-451, respectively. Twelve models, from a total of 78 test structures, were chosen from SSC-451. These are equivalent to those used in the present study in terms of structural dimensions and material properties, although they were fabricated by fusion welding.
Figure 3.6 Nomenclature of the structural dimensions
Table 3.6(a) Details of the principal dimensions of the test structures used in the present study

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<th>Model</th>
<th>Plate</th>
<th>Extrusion</th>
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<td>a (mm)</td>
<td>b (mm)</td>
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<td>19A</td>
<td>1200</td>
<td>300</td>
</tr>
<tr>
<td>20A</td>
<td>1200</td>
<td>300</td>
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</tr>
<tr>
<td>20C</td>
<td>1200</td>
<td>300</td>
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</table>
Table 3.6(b) Details of the principal dimensions of the test structures in SSC-451

<table>
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<td>b (mm)</td>
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<td>6</td>
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<td>1200</td>
<td>300</td>
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<td>31</td>
<td>1200</td>
<td>300</td>
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<tr>
<td>32</td>
<td>1200</td>
<td>300</td>
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3.2.2 Sectional Profiles and Properties of the Extrusions

The shapes and detailed dimensions of the extrusions in the test stiffened plate structures are indicated in Figure 3.7. A total of 10 different extrusion types were applied for the test structures in the present study and/or in SSC-451. Table 3.6 includes information on the extruded shapes for each of these structures. The cross-sectional properties of the extrusions and the plate panels for the present test structures and the SSC-451 test structures are indicated in Tables 3.7 and 3.8, respectively.

Tables 3.7(a) and 3.8(b) indicate the neutral axis measured from the outer surface of the plate (η) and the moment of inertia (I) calculated for a representative plate-stiffener combination, i.e., a single stiffener with attached plating. These parameters are involved in calculating the column slenderness ratio (λ) which is a primary parameter of the ultimate strength design formula for the entire stiffened plate.
structure.
For the purpose of the comparison, Tables 3.7(b) and 3.8(b) give exact solutions of the sectional properties such as the neutral axis ($\eta$), the moment of inertia ($I$), and the column slenderness ratio ($\lambda$) calculated for the entire stiffened panel section. It is found that the column slenderness ratio value calculated for the representative plate-stiffener combination model is sufficiently accurate.

In addition, it is noted that the related properties of the extrusions are exact solutions determined for actual cross sections with a non-uniform or varying wall thickness, instead of idealized sections that consist of a uniformly approximated wall thickness. The ratios of the plate and column slenderness for each of the test structures were computed from the following equations.

$$\beta = \frac{b}{t} \sqrt{\frac{\sigma_{Y_{eq1}}}{E}}, \quad \lambda = \frac{a}{r} \sqrt{\frac{\sigma_{Y_{eq2}}}{E}}, \quad \text{and} \quad r = \sqrt{\frac{I}{A_t}},$$

where $\sigma_{Y_{eq1}}$ = the equivalent yield strength of the plate part = \left(\sigma_{Yp}A_p + \sigma_{YS}A_{cp}\right) / \left(A_p + A_{cp}\right); \quad \sigma_{Y_{eq2}}$ = the equivalent yield strength of the entire cross section, including the plate and extrusions = \left(\sigma_{Yp}A_p + \sigma_{YS}A_s\right) / A_t; \quad \sigma_{Yp} = \text{the yield strength of the plate sheet}; \quad \sigma_{YS} = \text{the yield strength of the extrusions}; \quad E = \text{the elastic modulus}; \quad b = \text{plate breadth = stiffener spacing}; \quad t = \text{plate thickness}; \quad a = \text{the plate length between the transverse frames}; \quad A_p = \text{the total cross-sectional area of the plate part in the sheet}; \quad A_{cp} = \text{the total cross-sectional area of the plate part in the extrusions}; \quad A_{cs} = \text{the total cross-sectional area of the stiffener part in the extrusions}; \quad A_s = \text{the total cross-sectional area of the extrusions} = A_{cp} + A_{cs}; \quad \text{and} \quad A_t = \text{the total cross-sectional area of the entire plate panel} = A_p + A_s.$
Figure 3.7 (Continued) Cross-sectional profiles of the extrusions
Figure 3.7 (Continued) Cross-sectional profiles of the extrusions
Figure 3.7 (Continued) Cross-sectional profiles of the extrusions
Figure 3.7 (Continued) Cross-sectional profiles of the extrusions
Figure 3.7 (Continued) Cross-sectional profiles of the extrusions
Table 3.7(a) Details of the cross-sectional properties for a single stiffener with attached plating of the present test structures

<table>
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<tr>
<th>Model</th>
<th>$\sigma_Y$ (MPa)</th>
<th>$\sigma_S$ (MPa)</th>
<th>$\sigma_{Y_{eq}}$ (MPa)</th>
<th>$\sigma_{Y_{eq2}}$ (MPa)</th>
<th>$A_p$ (mm$^2$)</th>
<th>$A_{eq}$ (mm$^2$)</th>
<th>$A_{es}$ (mm$^2$)</th>
<th>$A_{s}$ (mm$^2$)</th>
<th>$A_{t}$ (mm$^2$)</th>
<th>$\eta$ (mm)</th>
<th>$I$ (cm$^4$)</th>
<th>$\beta$</th>
<th>$\lambda$</th>
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<td>19A</td>
<td>207.90</td>
<td>167.20</td>
<td>207.90</td>
<td>197.76</td>
<td>1800</td>
<td>0</td>
<td>597.42</td>
<td>597.42</td>
<td>2397.42</td>
<td>17.37</td>
<td>190.03</td>
<td>2.72</td>
<td>0.72</td>
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<td>167.20</td>
<td>210.33</td>
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Table 3.7(b) Details of the cross-sectional properties for the entire stiffened panel cross section of the present test structures

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<th>$\sigma_Y$ (MPa)</th>
<th>$\sigma_S$ (MPa)</th>
<th>$\sigma_{Y_{eq}}$ (MPa)</th>
<th>$\sigma_{Y_{eq2}}$ (MPa)</th>
<th>$A_p$ (mm$^2$)</th>
<th>$A_{eq}$ (mm$^2$)</th>
<th>$A_{es}$ (mm$^2$)</th>
<th>$A_{s}$ (mm$^2$)</th>
<th>$A_{t}$ (mm$^2$)</th>
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<th>$I$ (cm$^4$)</th>
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Table 3.8(a) Details of the cross-sectional properties for a single stiffener with attached plating of the SSC-451 test structures

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<th>$\sigma_{YS}$ (MPa)</th>
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<th>$A_{es}$ (mm²)</th>
<th>$A_s$ (mm²)</th>
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### Table 3.8(b) Details of the cross-sectional properties for the entire stiffened panel cross section of the SSC-451 test structures

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### 3.3 Fusion-welded Structures

Two of the test structure models, 19A and 20A, were fabricated via fusion welds. Figure 3.8 shows a schematic of fillet-type fusion welds. The welding conditions applied to fabricate these test structures were the same as those used to prepare the tensile coupon test specimens, as described in 3.1.3(b).

Figure 3.9 shows the layout of the fusion welds for test structures 19A and 20A. Figure 3.10 shows photos of the test structures during and after fusion fillet-weld fabrication. Test structure 20A is similar to 19A. Table 3.9 summarizes the weld types of the test structures in both the present study and SSC-451.

The fusion fillet-weld work of the present test structures was carried out by Best F.A Ltd. ([www.best-fa.co.kr](http://www.best-fa.co.kr)), Changwon, Korea, which is a company of professional fusion weld fabrication in Korea, while that of the SSC-451 test structures was performed by Hanjin Heavy Industries & Construction Co., Ltd. ([www.hanjinsc.com](http://www.hanjinsc.com)), Busan, Korea.
Figure 3.8 Schematic of fillet-type fusion weld (Fabrication method A)

Figure 3.9(a) Layout of test structure 19A for fillet-type fusion weld in mm

Figure 3.9(b) Layout of test structure 20A for fillet-type fusion weld in mm
Figure 3.10(a) Photo of one of the test structures during fusion-weld fabrication

Figure 3.10(b) Photo of test structure (19A) after fusion-weld fabrication
Table 3.9 Summary of fabrication methods applied in the test structures

<table>
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<th>The present test structures</th>
<th>The SSC-451 test structures</th>
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<td>GMAW - Method A</td>
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</table>

Note: Schematic of weld configurations

- **Fusion (GMAW) fillet-weld** (Fabrication method A)
- **Friction stir lap-weld** (fabrication method D)
- **Friction stir butt-weld** (Fabrication method C-2)
3.4 Friction Stir-Welded Structures
3.4.1 Classification of Fabrication Methods

The application of various FSW methods may be appropriate, as shown in Figure 3.11, and Figure 3.12 shows possible applications of FSW for the fabrication of stiffened plate structures. Table 3.9 summarizes the weld methods applied to fabricate the test structures.

In reality, however, FSW applications have a number of limitations that are associated with the intervention of the FSW machine in the target structures (including the plate and extrusions) to be fabricated. For the application of Method A (fillet-welding), which is the most widely used method for fusion welding, either the target structure or the FSW machine needs to be tilted about 25 degrees from the upright position as shown in Figure 3.12(a), although Method A can of course become relevant in the future.

Method B applies the butt-joining technique, but it is appropriate only for assembling individual extrusions with large flanges. Method C also applies the butt-joining technique, but only between the narrow plate sheets and the flanges of the extrusions.

Two types of Method C may be considered, namely C-1 and C-2. The method C-1 applies the FSW on the side of the extrusions, whereas the method C-2 applies it on the side of the plate sheet. When the breadth of the extruded flanges on the unwelded side is relatively large, compared to the FSW machine, it is difficult to apply Method C-1 because of possible intervention between the flange and the machine. Method D applies the lap-joining technique between the continuous plate sheet and the short flanges of the extrusions, although a deep penetration weld may be required.

During the fabrication of the test structures used in this project, the following difficulties arose.

- The FSW machine was fixed in the upright position to provide sufficient downward force during welding. There was no facility to tilt the target structure for FSW fillet-joining.
- No supplier could provide extrusions with large flanges for the application of Method B.
- The breadth of the extruded flanges on the unwelded side was relatively large, meaning that the application of Method C-1 was not relevant.

For these reasons, this study adopted Method C-2 (butt-joining), as shown in Figure 3.12(c), and Method D (lap-joining), as shown in Figure 3.12(d). The welding conditions were similar to those applied to prepare the tensile coupon test specimens, as described in 3.1.3(b), but with different sizes of the FSW tool, as indicated in Table 3.10. The FSW fabrication work of the present test structures was carried out by Winxen Co., Ltd. (www.winxen.com), Changwon, Korea, which is a FSW machine supplier in Korea under the supervision of the Welding Institute in the U.K.
Figure 3.11 Various joint configurations for FSW (Kramer 2007)

Figure 3.12(a) Schematic of FSW for fillet-joining between a continuous plate sheet and extrusions with taper flange (Method A)

Figure 3.12(b) Schematic of FSW for butt-joining between large extrusions only (Method B)
Figure 3.12(c) Schematic of FSW for butt-joining on the extrusion side between the plate sheet and the extrusion (Method C-1)

Figure 3.12(d) Schematic of FSW for butt-joining on the plate side between the plate sheet and the extrusion (Method C-2)

Figure 3.12(e) Schematic of FSW for lap-joining between the plate sheet and the extrusion (Method D)
Table 3.10 Sizes of the FSW tool applied to fabricate the test structures, with the nomenclature defined in Figure 3.4

<table>
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<th>d₃</th>
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<td>Lap-joining</td>
<td>5 mm</td>
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<td>8 mm</td>
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</table>

3.4.2 Butt-joining Methods

Figure 3.13 shows the layout of the friction stir welds for the butt-joining of test structures 19C and 20C. For the purposes of friction stir butt-welding, a specially designed jig was fabricated, as shown in Figure 3.14, in association with Method C-2. Figure 3.15 shows photos of one of the test structures during and after friction stir butt-joining.

Figure 3.13(a) Layout of test structure 19C for friction stir butt-joining in mm

Figure 3.13(b) Layout of test structure 20C for friction stir butt-joining in mm
Figure 3.14 Support jig design for FSW butt-joining in association with Method C-2 in mm

Figure 3.15(a) Photo of one of the test structures during friction stir butt-joining
3.4.3 Lap-joining Methods

Figure 3.16 shows the layout of the friction stir welds for the lap-joining of test structures 17D, 18D, 19D1, 19D2, 20D1 and 20D2. Figure 3.17 presents the design of the support jig for the friction stir lap-joining applied during fabrication of the test structures. Figure 18 shows a photo of test structure 17D after the completion of friction stir lap-joining.

Figure 3.15(b) Photo of test structure 19C after friction stir butt-joining

Figure 3.16(a) Layout of test structure 17D for friction stir lap-joining in mm
Figure 3.16(b) Layout of test structure 18D for friction stir lap-joining in mm

Figure 3.16(c) Layout of test structure 19D1 for friction stir lap-joining in mm

Figure 3.16(d) Layout of test structure 19D2 for friction stir lap-joining in mm

Figure 3.16(e) Layout of test structure 20D1 for friction stir lap-joining in mm
Figure 3.16(f) Layout of test structure 20D2 for friction stir lap-joining in mm

Figure 3.17 Support jig design for FSW lap-joining in association with Method D in mm
Figure 3.18(a) Photo of a test structure during friction stir lap-joining

Figure 3.18(b) Photo of test structure 17D after friction stir lap-joining
Chapter 4 Weld-induced Initial Imperfections of Test Structures

4.1 Types of Weld-induced Initial Imperfections

Welding may induce the following six types of initial imperfections in aluminum structures.

- Initial deflection of the plating between the stiffeners (see Figure 4.1)
- Column-type initial distortion of the stiffener (see Figure 4.1)
- Sideways initial distortion of the stiffener (see Figure 4.1)
- Residual stress in the plating between the stiffeners (see Figure 4.2)
- Residual stress in the stiffener web (see Figure 4.2)
- Softening in the thermo-mechanically affected zone (TMAZ) and the heat-affected zone (HAZ)

![Figure 4.1 Schematic of weld-induced initial distortions](image1)

![Figure 4.2(a) Schematic of fillet weld-induced residual stresses in the plating](image2)
It should be noted that the first five types of initial imperfections are also of primary concern in welded steel structures, although the softening phenomenon in the softened zone of these structures is usually insignificant and thus ignored in terms of ultimate compressive strength performance. The properties in the softened zone are often formulated in association with the reduced yield strength and breadth of this zone.

These weld-induced initial imperfections affect (reduce) the ultimate compressive strength performance of structures in a sensitive manner, and thus they must be dealt with as important parameters of influence in structural design and strength assessment.

The SSC-451 report (Paik et al. 2008b) presents an extensive set of initial imperfection measurements in aluminum stiffened plate structures fabricated by fusion welding. The fusion weld-induced initial imperfection measurements presented in SSC-451 are here compared with the database obtained from the present study by friction stir welding (FSW). The details of extrusion profiles and dimensions, and weld methods used to fabricate the present test structures are summarized in Tables 3.6(a) to 3.8(a) and Table 3.9.

### 4.2 SSC-451 Database

A total of 78 aluminum stiffened plate structures fabricated by fusion welding were studied in SSC-451 (Paik et al. 2008b), as indicated in Tables 3.6(b) to 3.8(b) and Table 3.9. The six types of weld-induced initial imperfections were measured for all of that study’s test structures, and the resulting database of measurements was then analyzed to obtain the statistical characteristics in terms of the means and standard deviations at the three levels of initial imperfections, i.e., slight, average and severe.

The following are the mean values of the initial imperfections obtained from the statistical analysis in SSC-451.

- Maximum initial deflection of the plating between longitudinal stiffeners:
\[ w_{opl} = \begin{cases} 0.018\beta^2t & \text{for slight level} \\ 0.096\beta^2t & \text{for average level} \\ 0.252\beta^2t & \text{for severe level} \end{cases} \quad (4.1) \]

• Maximum column-type initial distortion of the stiffener:

\[ w_{oc} = \begin{cases} 0.00016a & \text{for slight level} \\ 0.0018a & \text{for average level} \\ 0.0056a & \text{for severe level} \end{cases} \quad (4.2) \]

• Maximum sideways initial distortion of the stiffener:

\[ w_{os} = \begin{cases} 0.00019a & \text{for slight level} \\ 0.001a & \text{for average level} \\ 0.0024a & \text{for severe level} \end{cases} \quad (4.3) \]

• Compressive residual stress in the plating:

\[ \sigma_{rcx} = \begin{cases} -0.110\sigma_{yp} & \text{for slight level} \\ -0.161\sigma_{yp} & \text{for average level} \\ -0.216\sigma_{yp} & \text{for severe level} \end{cases} \quad (4.4) \]

• Compressive residual stress in the stiffener web:

\[ \sigma_{rcx} = \begin{cases} -0.078\sigma_{ys} & \text{for slight level} \\ -0.137\sigma_{ys} & \text{for average level} \\ -0.195\sigma_{ys} & \text{for severe level} \end{cases} \quad (4.5) \]

• Reduced yield strength in the softened zone (5083-H116):

\[ \frac{\sigma_{YHAZ}}{\sigma_{Y}} = \begin{cases} 0.906 & \text{for slight level} \\ 0.777 & \text{for average level} \\ 0.437 & \text{for severe level} \end{cases} \quad (4.6) \]
• Reduced yield strength in the softened zone (5383-H112):

\[
\frac{\sigma_{YHAZ}}{\sigma_Y} = 0.891 \quad \text{for average level}.
\]

(4.7)

• Reduced yield strength in the softened zone (5383-H116):

\[
\frac{\sigma_{YHAZ}}{\sigma_Y} = \begin{cases} 
0.820 & \text{for slight level} \\
0.774 & \text{for average level} \\
0.640 & \text{for severe level}
\end{cases}
\]

(4.8)

• Reduced yield strength in the softened zone (6082-T6):

\[
\frac{\sigma_{YHAZ}}{\sigma_Y} = 0.703 \quad \text{for average level}.
\]

(4.9)

• Half of the softened zone breadth:

\[
b_{HAZ} = b_t = \begin{cases} 
11.3\,\text{mm} & \text{for slight level} \\
23.1\,\text{mm} & \text{for average level} \\
29.9\,\text{mm} & \text{for severe level}
\end{cases}
\]

(4.10)

4.3 Initial Distortions

The three types of initial distortions, i.e., plate initial deflections, column-type initial distortions of the stiffeners, and sideways initial distortions of the stiffeners, were measured at various locations on the structures at intervals of 50 mm.

Figure 4.3 shows photos of the initial distortion measurements. Figure 4.4 presents three-dimensional displays of the initial distortion measurements for the plating and stiffeners in the test structures, where the measured values of the initial distortions were amplified by 30 times. Figure 4.5 depicts the initial distortion patterns for the plating and stiffeners at \( y = 0\,\text{mm} \) (the end of the structure) and \( y = 600\,\text{mm} \) (mid-span). It can be observed from Figure 4.5 that the initial distortions in the fusion-welded structures (19A, 20A) generally tended to be more severe than those in the FSW structures. It is also interesting to note that the initial distortions of the FSW butt-joined structures (19C, 20C) were more severe than those of the FSW lap-joined structures.

Figure 4.6 presents the details of the initial distortion measurements, and Table 4.1 lists the maximum values of the initial distortions in the plating and stiffeners. The acceptance tolerances of the weld-induced initial distortions in aluminum structures, as specified by classification society rules (ABS 2006), are also compared in this table, indicating that the maximum initial distortions in the test structures were within these tolerances.
Figure 4.3 (a) Photo of the set-up for the plate initial deflection measurements

Figure 4.3(b) Photo of the set-up for the stiffener initial distortion measurements
Figure 4.4(a) Three-dimensional display of initial distortions (amplified by 30 times) in test structure 19A

Figure 4.4(b) Three-dimensional display of initial distortions (amplified by 30 times) in test structure 20A

Figure 4.4(c) Three-dimensional display of initial distortions (amplified by 30 times) in test structure 17D

Figure 4.4(d) Three-dimensional display of initial distortions (amplified by 30 times) in test structure 18D
Figure 4.4(e) Three-dimensional display of initial distortions (amplified by 30 times) in test structure 19D1

Figure 4.4(f) Three-dimensional display of initial distortions (amplified by 30 times) in test structure 19D2

Figure 4.4(g) Three-dimensional display of initial distortions (amplified by 30 times) in test structure 20D1

Figure 4.4(h) Three-dimensional display of initial distortions (amplified by 30 times) in test structure 20D2
Figure 4.4(i) Three-dimensional display of initial distortions (amplified by 30 times) in test structure 19C

Figure 4.4(j) Three-dimensional display of initial distortions (amplified by 30 times) in test structure 20C

Figure 4.5(a) Shape of initial distortions (amplified by 30 times) for the plating and stiffeners in test structure 19A

Figure 4.5(b) Shape of initial distortions (amplified by 30 times) for the plating and stiffeners in test structure 20A
Figure 4.5(c) Shape of initial distortions (amplified by 30 times) for the plating and stiffeners in test structure 17D

Figure 4.5(d) Shape of initial distortions (amplified by 30 times) for the plating and stiffeners in test structure 18D

Figure 4.5(e) Shape of initial distortions (amplified by 30 times) for the plating and stiffeners in test structure 19D1

Figure 4.5(f) Shape of initial distortions (amplified by 30 times) for the plating and stiffeners in test structure 19D2

Figure 4.5(g) Shape of initial distortions (amplified by 30 times) for the plating and stiffeners in test structure 20D1
Figure 4.5(h) Shape of initial distortions (amplified by 30 times) for the plating and stiffeners in test structure 20D2

Figure 4.5(i) Shape of initial distortions (amplified by 30 times) for the plating and stiffeners in test structure 19C

Figure 4.5(j) Shape of initial distortions (amplified by 30 times) for the plating and stiffeners in test structure 20C
Table 4.1 Maximum values of the initial distortion measurements in the plating and stiffeners, together with the ABS rule requirements for tolerance

<table>
<thead>
<tr>
<th>Model</th>
<th>$w_{oa}$ (mm)</th>
<th>$w_{oc}$ (mm)</th>
<th>$w_{os}$ (mm)</th>
<th>Tolerance (mm)</th>
</tr>
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<tr>
<td></td>
<td>Plate</td>
<td>Stiffener</td>
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<td></td>
</tr>
<tr>
<td>19A</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>-1.527</td>
<td>-0.635</td>
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<td></td>
</tr>
<tr>
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<td>-1.254</td>
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<td>0.950</td>
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</tr>
<tr>
<td>20A</td>
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</tr>
<tr>
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</tr>
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<td>-0.872</td>
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(a) $y = 750\text{mm}$, $\frac{w_{opt}}{t} = 0.125$

(b) $y = 450\text{mm}$, $\frac{w_{opt}}{t} = 0.150$

(c) $y = 150\text{mm}$, $\frac{w_{opt}}{t} = 0.209$

(a) $y = 900\text{mm}$, $\frac{w_{oc}}{a} = 0.0002$

(b) $y = 600\text{mm}$, $\frac{w_{oc}}{a} = 0.0020$

(c) $y = 300\text{mm}$, $\frac{w_{oc}}{a} = 0.0014$

(d) $y = 0\text{mm}$, $\frac{w_{oc}}{a} = 0.0013$

(a) $y = 900\text{mm}$, $\frac{w_{os}}{a} = 0.0008$
Figure 4.6(a) Details of initial distortion measurements in test structure 19A
Figure 4.6(b) Details of initial distortion measurements in test structure 20A
(b) y = 450mm, \( w_{opt}/t = 0.187 \)

(c) y = 150mm, \( w_{opt}/t = 0.120 \)

(a) y = 900mm, \( w_{oc}/a = 0.0003 \)

(b) y = 600mm, \( w_{oc}/a = 0.0011 \)

(c) y = 300mm, \( w_{oc}/a = 0.0009 \)

(d) y = 0mm, \( w_{oc}/a = 0.0003 \)

(a) y = 900mm, \( w_{os}/a = 0.0004 \)

(b) y = 600mm, \( w_{os}/a = 0.0002 \)

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Figure 4.6(c) Details of initial distortion measurements in the test structure 17D
Figure 4.6(d) Details of initial distortion measurements in test structure 18D
Figure 4.6(e) Details of initial distortion measurements in test structure 19D1
(a) $y = 750\text{mm}, \frac{w_{\text{opt}}}{t} = 0.146$

(b) $y = 450\text{mm}, \frac{w_{\text{opt}}}{t} = 0.122$

(c) $y = 150\text{mm}, \frac{w_{\text{opt}}}{t} = 0.115$

(d) $y = 0\text{mm}, \frac{w_{\text{opt}}}{a} = 0.0004$

(e) $y = 900\text{mm}, \frac{w_{\text{opt}}}{a} = 0.0004$

(f) $y = 600\text{mm}, \frac{w_{\text{opt}}}{a} = 0.0008$

(g) $y = 300\text{mm}, \frac{w_{\text{opt}}}{a} = 0.0004$

(h) $y = 0\text{mm}, \frac{w_{\text{opt}}}{a} = 0.0004$

(i) $y = 900\text{mm}, \frac{w_{\text{opt}}}{a} = 0.0002$
Figure 4.6(f) Details of initial distortion measurements in test structure 19D2
Figure 4.6(g) Details of initial distortion measurements in test structure 20D1
Figure 4.6(h) Details of initial distortion measurements in test structure 20D2
Figure 4.6(i) Details of initial distortion measurements in test structure 19C
4.4 Residual Stresses

The hole-drilling strain-gauge method (Inter Technology 2005) is the most widely-used modern technique applied today to measure residual stresses. Therefore, this method was employed to measure the weld-induced residual stresses in the test structures in the present study and those in SSC-451.

The residual stress measurement procedure involves the following six steps (Inter Technology 2005).

- Step 1: A special three- (or six-) element strain-gauge rosette is installed at the target location where the residual stresses are to be measured.
- Step 2: The gauge grids are wired and connected to a multi-channel static strain indicator or through a switch-and-balance unit (six-element gauge).
- Step 3: A precision milling guide is attached to the test part and accurately centered over a drilling target on the rosette.
- Step 4: After zero-balancing the gauge circuits, a small, shallow hole is drilled through the geometric center of the rosette.
- Step 5: Readings are taken of the relaxed strains that correspond to the residual stress.
- Step 6: Using special data-reduction relationships, the principal residual stresses and their angular orientations are calculated from these measured strains.

Figure 4.7 shows the residual stress measurement set-up using the hole-drilling strain-gauge method. With regard to Step 4, the hole was drilled in the target location up to a depth of 2.3 mm in the plate thickness direction where the released strain became almost constant. Figure 4.8 shows typical examples of the relationship between the drilling depth and the released strain in the panel longitudinal direction at a location in the compressive residual stress zone.

It was found that there is no change in the released strain after a drilling depth of 2.0 mm, regardless of the fabrication method used. It is also interesting to note that this strain (and the subsequent compressive residual stress) was greater in the following order: GMAW (19A), FSW (19D2) and FSW (19C).

Figure 4.9 shows the residual stress distributions, both measured and as idealized for the test structures. The idealized distributions of the residual stress were determined based on the hypothesis that the compressive residual stress must be in equilibrium with the tensile residual stress over the cross-sectional area in the plating or stiffener web.
Figure 4.7 Set-up for residual stress measurement using the hole-drilling strain-gauge method
Figure 4.8 Relationships between drilling depth and released strain in the panel longitudinal direction at a location in the compressive residual stress zone.

Figure 4.9(a) Distribution of residual stress in test structure 19A.
Figure 4.9(b) Distribution of residual stress in test structure 20A: (a) plate, (b) stiffener web
Figure 4.9(c) Distribution of residual stress in test structure 17D

Figure 4.9(d) Distribution of residual stress in test structure 18D
Figure 4.9(e) Distribution of residual stress in test structure 19D1

Figure 4.9(f) Distribution of residual stress in test structure 19D2
Figure 4.9(g) Distribution of residual stress in test structure 20D1: (a) plate, (b) stiffener web
Figure 4.9(h) Distribution of residual stress in test structure 20D2: (a) plate, (b) stiffener web
Figure 4.9(i) Distribution of residual stress in test structure 19C

Figure 4.9(j) Distribution of residual stress in test structure 20C
4.5 Properties of the Softened Zone

The micro-structural characteristics of the TMAZ may differ from those of the HAZ, as is illustrated in Figure 2.7 in Chapter 2. For the sake of simplicity, however, the present study applies the following hypotheses.

- The properties of the TMAZ are similar to those of the HAZ. This is because the two zones exhibit a similar tendency in terms of reduced yield strength, which is of primary concern when evaluating ultimate compressive strength performance.
- The yield strength in the softened zone is equivalent to the tensile residual stress in the corresponding zone. This is based on the fact that the tensile residual stress in the HAZ easily reaches the material yield stress in the case of mild steel (Masubuchi 1980, Paik & Thayamballi 2003).
- The compressive residual stress is in equilibrium with the tensile residual stress over the plate cross-sectional area.

Table 4.2 Mechanical properties of the softened zone in terms of breadth and reduced yield strength

<table>
<thead>
<tr>
<th>Model</th>
<th>Full breadth of the softened zone (mm)</th>
<th>Reduced yield strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plate</td>
<td>Web</td>
</tr>
<tr>
<td>19A</td>
<td>45.06</td>
<td>23.32*</td>
</tr>
<tr>
<td>20A</td>
<td>44.78</td>
<td>23.32</td>
</tr>
<tr>
<td>17D</td>
<td>37.70</td>
<td>2.67*</td>
</tr>
<tr>
<td>18D</td>
<td>36.02</td>
<td>2.49*</td>
</tr>
<tr>
<td>19D1</td>
<td>33.76</td>
<td>2.69*</td>
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<tr>
<td>19D2</td>
<td>39.68</td>
<td>2.69*</td>
</tr>
<tr>
<td>20D1</td>
<td>34.74</td>
<td>4.74</td>
</tr>
<tr>
<td>20D2</td>
<td>38.94</td>
<td>4.74</td>
</tr>
<tr>
<td>19C</td>
<td>16.96</td>
<td>0.0*</td>
</tr>
<tr>
<td>20C</td>
<td>19.40</td>
<td>0.0*</td>
</tr>
</tbody>
</table>

Note: *Assumed values; the rest are measured values.

Table 4.2 summarizes the mechanical properties of the softened zone in terms of breadth and reduced yield strength. All of the properties of the plate part are obtained from direct measurements. The properties of the stiffener web are mostly
assumed where the reduced yield strength in the softened zone of the stiffener web is considered to be 90% of the yield strength of the base material from the measurements indicated in Figures 4.9(g) and 4.9(h).

Table 4.3 Comparison of initial imperfections in fusion welds versus friction stir welds

<table>
<thead>
<tr>
<th>Model</th>
<th>( w_{opl}/(\beta^2 t) )</th>
<th>( w_{oc}/a )</th>
<th>( w_{ev}/a )</th>
<th>( \sigma_{wca}/\sigma_{yp} )</th>
<th>( \sigma_{YHAZ}/\sigma_{yp} )</th>
<th>( b_{HAZ} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>19A</td>
<td>0.022</td>
<td>0.0012</td>
<td>0.00051</td>
<td>-0.179</td>
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</tr>
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<tr>
<td>17D</td>
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<td>0.00027</td>
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<td>0.978</td>
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</tr>
<tr>
<td>18D</td>
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<td>-0.165</td>
<td>0.978</td>
<td>18.01</td>
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</tr>
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</table>

Note: 1) Indicates the average values of initial imperfections due to fusion fillet-welds, obtained from SSC-451.

It is confirmed that the 1 inch rule applies in terms of the breadth of the softened zone for fusion welds (Models 19A and 20A), as is also indicated in Equation (4.10). For FSW structures, however, it is found that the breadth of the softened zone is equivalent to approximately two times the width of the FSW tool shoulder for lap-joining, where the width of the FSW tool shoulder is denoted by \( d_3 \), as defined in Figure 3.4 in Chapter 3, and the breadth of this zone for butt-joining is equivalent to the width of the FSW tool shoulder.

It should be noted that the softened zone properties presented in Table 4.2 are used for the nonlinear finite element method computations of ultimate strength that are discussed in Chapter 6.

4.6 Comparison between Fusion Welds and Friction Stir Welds

The weld-induced initial imperfections of FSW aluminum structures are here compared with those of fusion fillet-welded aluminum structures.
Figure 4.10(a) Comparison of the maximum initial distortion of the plating in fusion welds versus friction stir welds.

Figure 4.10(b) Comparison of the maximum column-type initial distortion of the stiffener in fusion welds versus friction stir welds.
Figure 4.10(c) Comparison of the maximum sideways initial distortion of the stiffener in fusion welds versus friction stir welds

- Maximum sideways initial distortion of stiffener
  - Fusion weld average level (0.001)
  - Fusion weld slight level (0.000019)

Figure 4.10(d) Comparison of the compressive residual stress at the plating in fusion welds versus friction stir welds

- Compressive residual stress at plating
  - Fusion weld slight level (-0.110)
  - Fusion weld average level (-0.161)
Figure 4.10(e) Comparison of the reduced yield strength in the softened zone in fusion welds versus friction stir welds.

Figure 4.10(f) Comparison of the softened zone breadth (half value) in fusion welds versus friction stir welds.
Table 4.3 and Figure 4.10 present the average values of these initial imperfections, as obtained from the measurements of the test structures in the present study, as well as the slight and average values of the initial imperfections obtained from SSC-451 by fusion fillet-welds (GMAW).

The insights and findings obtained from this comparison of the initial imperfections in fusion fillet-welds versus friction stir lap- and butt-welds are as follows.

• The FSW-induced initial distortions are, in general, smaller than the fusion-weld induced initial distortions. The plate initial deflection due to friction stir welds is close to the slight level of such deflection due to fusion fillet-welds. The column-type or sideways initial distortion of the stiffeners due to friction stir welds is some 50% of that due to fusion fillet-welds.

• It is observed that the level of the sideways initial distortions of the stiffeners due to FSW butt-joining for test structures 19C and 20C appears to be comparatively large. It is thought, however, that these distortions were inherent in the extrusion production process for these structures rather than arising during FSW. The extrusions of test structures 19C and 20C had wide flanges that may exhibit non-uniform temperature distribution over the flange and web during the cooling process, thus causing larger sideways initial distortions than those in extruded short flanges.

• The level of the compressive residual stress in FSW lap-welds is similar to that in fusion fillet-welds, but the level of the compressive residual in FSW butt-welds is closer to the slight level in fusion fillet-welds.

• The trend in the yield strength reduction in the softened zone depends on the material type. The reduction in this zone due to friction stir welds is similar to that due to fusion welds.

• The breadth of the softened zone in FSW aluminum structures is equal to approximately two times the width of the FSW tool shoulder for lap-joining, but approximately equal to the width of the FSW tool shoulder for butt-joining. This may be because the lap-joining process requires a deeper penetration of the FSW pin than does the butt-joining process, and, subsequently, the HAZ tends to be more likely to expand.
Chapter 5 Buckling Collapse Testing

5.1 Test Facilities and Their Set-up

Buckling collapse testing on the stiffened plate structures was performed in a test frame that facilitates a 2000 kN loading actuator at the Ship and Offshore Structural Mechanics Laboratory, the Lloyd’s Register Educational Trust (LRET) Research Centre of Excellence at Pusan National University.

Figure 5.1 shows a typical test structure set-up using this facility. The target structure was positioned vertically in the test frame. The loading actuator generated axial compressive forces in the longitudinal direction of the test plate panels. To apply these forces uniformly over the cross-sectional area of the loaded panel edges, a rigid steel plate was attached to each of the loaded panel edges.

Both the loaded and unloaded edges of the test structures were kept straight and in a simply supported condition, i.e., with zero lateral deflection and zero rotational restraints, during testing.

To accomplish the simply supported condition at the loaded edges, a rigid solid bar with a circular cross section was inserted into each edge, as shown in Figure 5.2. The unloaded edges were supported by a set of two rigid strips bolted to the test panels, as shown in Figure 5.3.

Figure 5.1 Photo of the test set-up for buckling collapse testing
Figure 5.2 Photo of the rigid solid bar inserted into the loaded edge

Figure 5.3 Photo of the rigid strips bolted to the test panel at the unloaded edge
The axial compressive forces were applied at the neutral axis of the panel cross section, as shown in Figure 5.2, until and after the test structure had reached its ultimate strength. This was important in avoiding any unnecessary eccentricity-causing additional end moments and ensuring that pure axial compressive forces could be applied. The neutral axis of each test structure was determined using structural mechanics before the start of buckling collapse testing.

It was also important to confirm the precision of the test set-up for each of the test structures in which the test plate panels were subjected to pure and uniform axial compressive forces. For this purpose, a total of eight strain gauges were attached to the plating and stiffeners at both the lower and upper ends of each structure, as shown in Figure 5.4. The axial strains of the structures were measured until axial compressive forces of some 150 kN had been reached, with comparisons made among them, and the neutral axis position of each of those in the test frame was readjusted until the axial strains become almost identical. This was repeated prior to starting the actual buckling collapse testing. However, it was impossible to adjust the change of the neutral axis position in the middle of buckling collapse testing, which can occur due to the local failure of test structures.

The relationships between the axial force and axial displacement of the test structures were recorded with a personal computer. Photographs of the test structures were taken before, during and after ultimate strength was reached.
5.2 Test Results and Discussions

It is recognized that the following six types of collapse modes are relevant to stiffened plate structures until ultimate strength is reached (Paik & Thayamballi 2003, Paik & Thayamballi 2007).

- **Mode I**: Overall collapse after overall buckling, see Figure 5.5(a)
- **Mode II**: Collapse of plating between stiffeners without failure of stiffeners, see Figure 5.5(b)
- **Mode III**: Beam-column type collapse as a plate-stiffener combination, see Figure 5.5(c)
- **Mode IV**: Local buckling of stiffener web, see Figure 5.5(d)
- **Mode V**: Flexural-torsional buckling (tripping) of stiffener, see Figure 5.5(e)
- **Mode VI**: Gross yielding without local buckling

![Figure 5.5(a)](image1)
**Figure 5.5(a) Mode I: Overall collapse after overall buckling**

![Figure 5.5(b)](image2)
**Figure 5.5(b) Mode II: Collapse of plating without failure of stiffeners**
Figure 5.5(c) Mode III: Beam-column type collapse as a plate-stiffener combination

Figure 5.5(d) Mode IV: Local buckling of stiffener web

Figure 5.5(e) Mode V: Flexural-torsional buckling (tripping) of stiffener
Table 5.1 Summary of the ultimate compressive strength and associated collapse mode of the present test structures

<table>
<thead>
<tr>
<th>Model (Fig. No.)</th>
<th>$P_p$ (kN)</th>
<th>$P_u$ (kN)</th>
<th>$P_u/P_p$</th>
<th>Collapse mode</th>
<th>Delamination failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>19A (5.6)</td>
<td>1646.9</td>
<td>697.1</td>
<td>0.423</td>
<td>V</td>
<td>No delam</td>
</tr>
<tr>
<td>20A (5.7)</td>
<td>2139.7</td>
<td>1401.1</td>
<td>0.655</td>
<td>IV</td>
<td>No delam</td>
</tr>
<tr>
<td>17D (5.8)</td>
<td>2009.4</td>
<td>1006.4</td>
<td>0.501</td>
<td>III</td>
<td>One severe delam in post-ULS</td>
</tr>
<tr>
<td>18D (5.9)</td>
<td>2003.8</td>
<td>1036.2</td>
<td>0.517</td>
<td>III</td>
<td>Two severe delams in post-ULS</td>
</tr>
<tr>
<td>19D1 (5.10)</td>
<td>2095.5</td>
<td>1111.9</td>
<td>0.531</td>
<td>III</td>
<td>Two severe and one slight delams in post-ULS</td>
</tr>
<tr>
<td>19D2 (5.11)</td>
<td>1847.8</td>
<td>939.7</td>
<td>0.509</td>
<td>IV</td>
<td>One slight delam in post-ULS</td>
</tr>
<tr>
<td>20D1 (5.12)</td>
<td>3161.6</td>
<td>1563.7</td>
<td>0.495</td>
<td>V</td>
<td>Two severe delams before ULS</td>
</tr>
<tr>
<td>20D2 (5.13)</td>
<td>2299.8</td>
<td>1561.9</td>
<td>0.679</td>
<td>IV</td>
<td>Three slight delams in post-ULS</td>
</tr>
<tr>
<td>19C (5.14)</td>
<td>1583.5</td>
<td>784.6</td>
<td>0.495</td>
<td>II</td>
<td>Two severe and one slight delams in post-ULS</td>
</tr>
<tr>
<td>20C (5.15)</td>
<td>1999.1</td>
<td>1166.0</td>
<td>0.583</td>
<td>IV</td>
<td>Two severe and one slight delams before ULS</td>
</tr>
</tbody>
</table>

Note: $P_u$ = ultimate compressive force; $P_p$ = fully plastic axial force = $\sum A_i\sigma_{Y_i}$, with $A_i$ = area of (i)th cross-section and $\sigma_{Y_i}$ = material yield strength of the (i)th cross-section.

In the following sections, the buckling collapse strength characteristics of each of the test structures are described, where the details of extrusion profiles and dimensions, and weld methods are indicated in Tables 3.6(a) to 3.8(a) and Table 3.9. Table 5.1 summarizes the ultimate compressive strength and associated collapse mode of the test structures obtained from the buckling collapse testing.

5.2.1 Fusion Fillet-welded Structures 19A and 20A

Figures 5.6(a) and 5.7(a) show the relationships between the axial compressive
force and axial compressive displacement for test structures 19A and 20A, respectively. The fully plastic axial force of each structure without consideration of buckling is also plotted. The details of the test structures in terms of material type, extrusion type, and weld method together with the structural dimensions are described in Chapter 3.

The ultimate compressive strength ($P_u$) normalized by the fully plastic force ($P_p$) is indicated in Table 5.1. The ultimate strength ratio to the fully plastic axial force is an indicator of representing the severity of local failures in which the ultimate strength ratio becomes smaller as local failure occurs earlier and/or more severely.

Test structure 19A reached its ultimate strength via Collapse Mode V (tripping), as shown in Figure 5.6(b), while test structure 20A collapsed via Mode IV (local buckling of stiffener web), as shown in Figure 5.7(b). No local failure including delamination in the fusion welded area occurred in both 19A and 20A until and after ultimate strength had been reached.

![Model 19A](image)

**Figure 5.6(a) Relationship between axial compressive force and axial compressive displacement for test structure 19A**
Figure 5.6(b) Photo of Collapse Mode V in test structure 19A
Figure 5.7(a) Relationship between axial compressive force and axial compressive displacement for test structure 20A

Model 20A

$P_p = 2139.7$ kN

$P_u = 1404.1$ kN

$P_u$: Ultimate strength

$P_p$: Full plastic strength

Displacement (mm)

Force (kN)
5.2.2 FSW Lap-joined Structures 17D, 18D, 19D1, 19D2, 20D1 and 20D2

Figures 5.8(a) to 5.13(a) show the relationships between the axial compressive force and axial compressive displacement for test structures 17D, 18D, 19D1, 19D2, 20D1, and 20D2, respectively. The fully plastic axial force of each structure without consideration of buckling is also plotted. The ultimate strength of each structure normalized by the fully plastic capacity is presented in Table 5.1.

Each of three test structures 17D, 18D and 19D1 reached its ultimate strength via Collapse Mode III (beam column-type collapse), as shown in Figure 5.8(b). Test structure 20D1 showed Collapse Mode V (flexural-torsional buckling of the stiffener) similar to that as shown in Figure 5.6(b), while test structures 19D2 and 20D2 reached their ultimate strength via Collapse Mode IV (local buckling of stiffener web) similar to that as shown in Figure 5.7(b).

For all the FSW lap-joined test structures, delamination occurred across the entire width of the friction stir-welded area of stiffeners, as those shown in Figures 5.8(b) to 5.13(b) which are photos taken at the end of testing. Most structures showed the delamination failure after ultimate strength had been reached. However, in test structure 20D1, severe delamination in two stiffeners occurred, starting before the ultimate compressive strength had been reached.

It is surmised that such a delamination must have contributed to the collapse of this structure to some large extent. In fact, the ultimate strength ratio of test structure 20D1 to the fully plastic axial force is unusually small as will be discussed in Chapter 6, by a comparison with nonlinear finite element method computations.

This caused speculation about the quality of the friction stir-welding (FSW) lap-
joining technology, although the delamination mostly occurred after the structures had reached ultimate strength, except for one structure, i.e., 20D1.

The post-collapse delamination in lap-welded structures, i.e., with base plate and extruded stiffeners, may not be of major concern because it can still maintain the water tightness of the stiffened plate structures. However, the pre-collapse delamination can reduce the ultimate compressive strength significantly.

It is recognized that the performance of friction stir-welded region is significantly affected by the welding parameters such as width and depth of molten metal thin layer, molten temperature, rotating and forwarding speeds, and possible quick cooling, etc. (Cavaliere et al. 2009, Lombard et al. 2009, Zhang & Zhang 2009a, 2009b). Therefore, further study is required to establish optimum parameters of the FSW process and also investigate the compressive strength properties and delamination in the friction stir lap-welded region.

![Figure 5.8(a) Relationship between axial compressive force and axial compressive displacement for test structure 17D](image)

**Model 17D**

- $P_u = 1006.4\text{kN}$
- $P_p = 2009.4\text{kN}$

$P_u$: Ultimate strength

$P_p$: Full plastic strength

**Figure 5.8(a) Relationship between axial compressive force and axial compressive displacement for test structure 17D**
Figure 5.8(b) Photo of Collapse Mode III in test structure 17D

Delamination length= 140mm

Model 17D

Severe

Figure 5.8(c) Photo of the delamination failure in test structure 17D, taken at the end of testing
Model 18D

- $P_u = 1036.2 \text{kN}$
- $P_p = 2003.8 \text{kN}$

Experiment

$P_u$: Ultimate strength
$P_p$: Full plastic strength

Figure 5.9(a) Relationship between axial compressive force and axial compressive displacement for test structure 18D
Figure 5.9(b) Photo of the delamination failure in test structure 18D, taken at the end of testing
Figure 5.10(a) Relationship between axial compressive force and axial compressive displacement for test structure 19D1

Model 19D1

Pu: Ultimate strength
Pp: Full plastic strength

Pu = 1111.9 kN
Pp = 2095.5 kN

Displacement (mm)

Force (kN)
Figure 5.10(b) Photo of the delamination failure in test structure 19D1, taken at the end of testing
Model 19D2

\[ P_p = 1847.8 \text{kN} \]

\[ P_u = 939.7 \text{kN} \]

Figure 5.11(a) Relationship between axial compressive force and axial compressive displacement for test structure 19D2

Pu: Ultimate strength
Pp: Full plastic strength
Figure 5.11(b) Photo of the delamination failure in test structure 19D2, taken at the end of testing
Figure 5.12(a) Relationship between the axial compressive force and axial compressive displacement for test structure 20D1
Figure 5.12(b) Photo of the delamination failure in test structure 20D1, taken at the end of testing.
Figure 5.13(a) Relationship between axial compressive force and axial compressive displacement for test structure 20D2

- Model 20D2
  - $P_p = 2299.8\text{kN}$
  - $P_u = 1561.9\text{kN}$

$P_u$: Ultimate strength
$P_p$: Full plastic strength
5.2.3 FSW Butt-joined Structures 19C and 20C

Figures 5.14(a) and 5.15(a) show the relationships between the axial compressive force and axial compressive displacement for test structures 19C and 20C, respectively. The fully plastic axial force without consideration of buckling is also plotted. The ultimate strength of these structures normalized by the fully plastic capacity is indicated in Table 5.1. Test structure 19C reached its ultimate strength via Collapse Mode II (collapse of the plating without failure of the stiffeners), as shown in Figure 5.14(b), while test structure 20C showed Collapse Mode IV (local buckling of stiffener web), as shown in Figure 5.15(b).

Delamination also occurred in the FSW butt-joined area between plates, as those shown in Figure 5.14(c) and 5.15(b). Test structure 19C showed delamination after the ultimate strength had been reached, but delamination occurred in test structure 20C prior to the ultimate strength. Again, it is thought that the ultimate strength of test structure 20C is unusually small compared to nonlinear finite element computations presented in Chapter 6.

Figure 5.13(b) Photo of the delamination failure in test structure 20D2, taken at the end of testing
It is interesting to note that the delaminations in the friction stir butt-welds have occurred only at one free edge of the butt joint but not at both free edges, with the configuration of the butt welds described in Table 3.9 of Chapter 3.

The pre-collapse delamination in friction stir butt-welded structures can of course reduce the ultimate compressive strength performance significantly. Also, the pre- or post-collapse delamination in friction stir butt-welded structures should be of great concern because the water tightness of the stiffened plate structure can not be assured anymore. In this regard, the friction stir lap-weld method may be more promising than the friction stir butt-weld method, because the post-collapse delamination is not of major concern in the friction stir lap-welded structures.
Further study is recommended to manage the quality assurance in the friction stir butt-welded region in association with the mechanical property and delamination, similar to the friction stir lap-welded region as described in Section 5.2.2.

Figure 5.14(b) Photo of Collapse Mode II in test structure 19C
Figure 5.14(c) Photo of the delamination failure in test structure 19C, taken at the end of testing
Figure 5.15(a) Relationship between axial compressive force and axial compressive displacement for test structure 20C

Model 20C

$P_p = 1999.1 \text{kN}$

$P_u = 1166.0 \text{kN}$

$P_u$: Ultimate strength

$P_p$: Full plastic strength

Displacement (mm)

Force (kN)
Figure 5.15(b) Photo of Collapse Mode IV in test structure 20C

Figure 5.15(c) Photo of the delamination failure in test structure 20C, taken at the end of testing
5.3 SSC-451 Database

Figures 5.16 to 5.27 show the relationships between the axial compressive force and axial compressive displacement for the fusion-welded test structures in SSC-451, until and after ultimate strength had been reached, where the details of the extrusion profiles and dimensions, and weld methods are indicated in Tables 3.6(b) to 3.8(b) and Table 3.9. Table 5.2 summarizes the ultimate compressive strength and associated collapse mode of the structures.

<table>
<thead>
<tr>
<th>Model (Fig. No.)</th>
<th>P_p (kN)</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P_u (kN)</td>
<td>P_u/P_p</td>
</tr>
<tr>
<td>5 (5.16)</td>
<td>1831.3</td>
<td>777.8</td>
</tr>
<tr>
<td>6 (5.17)</td>
<td>1831.2</td>
<td>918.0</td>
</tr>
<tr>
<td>7 (5.18)</td>
<td>1903.4</td>
<td>931.8</td>
</tr>
<tr>
<td>8 (5.19)</td>
<td>2482.8</td>
<td>1513.8</td>
</tr>
<tr>
<td>17 (5.20)</td>
<td>2049.0</td>
<td>778.0</td>
</tr>
<tr>
<td>18 (5.21)</td>
<td>2048.8</td>
<td>829.6</td>
</tr>
<tr>
<td>19 (5.22)</td>
<td>2160.5</td>
<td>970.5</td>
</tr>
<tr>
<td>20 (5.23)</td>
<td>3057.1</td>
<td>1659.2</td>
</tr>
<tr>
<td>29 (5.24)</td>
<td>1645.1</td>
<td>791.0</td>
</tr>
<tr>
<td>30 (5.25)</td>
<td>1645.0</td>
<td>908.7</td>
</tr>
<tr>
<td>31 (5.26)</td>
<td>1717.2</td>
<td>895.9</td>
</tr>
<tr>
<td>32 (5.27)</td>
<td>2296.6</td>
<td>1367.3</td>
</tr>
</tbody>
</table>

Note: \( P_u \) = ultimate compressive force; \( P_p \) = fully plastic axial force = \( \sum A_i \sigma_{Y_i} \) where \( A_i \) = area of the (i)th cross-section and \( \sigma_{Y_i} \) = material yield strength of the (i)th cross-section.
All the test structures reached the ultimate strength by an anticipated collapse mode. Most structures showed one distinct collapse mode until ultimate strength had been reached, but test structures 19, 20, 31 and 32 collapsed via combined modes of III (beam-column type collapse) and IV (local buckling of stiffener web). No delamination failure occurred in the fusion welded area of all the SSC-451 test structures.

The ultimate compressive strength performance of these test structures was then compared with that for the FSW test structures investigated in the present project as discussed in Chapters 6 and 7.

![Graph showing the relationship between axial compressive force and axial compressive displacement for test structure 5 in SSC-451](image)

**Model 5**

- $P_u = 777.8 \text{kN}$
- $P_p = 1831.3 \text{kN}$

**Figure 5.16** Relationship between axial compressive force and axial compressive displacement for test structure 5 in SSC-451
Figure 5.17 Relationship between axial compressive force and axial compressive displacement for test structure 6 in SSC-451
Figure 5.18 Relationship between axial compressive force and axial compressive displacement for test structure 7 in SSC-451
Figure 5.19 Relationship between axial compressive force and axial compressive displacement for test structure 8 in SSC-451

Model 8

Pu = 1513.75 kN
Pp = 2482.8 kN

Pu: Ultimate strength
Pp: Full plastic strength
Figure 5.20 Relationship between axial compressive force and axial compressive displacement for test structure 17 in SSC-451

Model 17

$P_u = 778.0 \text{kN}$

$P_p = 2049.0 \text{kN}$

$P_u$: Ultimate strength

$P_p$: Full plastic strength

Displacement (mm)

Force (kN)
Figure 5.21 Relationship between axial compressive force and axial compressive displacement for test structure 18 in SSC-451

Model 18

$P_p = 2048.8\, \text{kN}$

$P_u = 829.6\, \text{kN}$

$P_u$: Ultimate strength

$P_p$: Full plastic strength
Figure 5.22 Relationship between axial compressive force and axial compressive displacement for test structure 19 in SSC-451
Figure 5.23 Relationship between axial compressive force and axial compressive displacement for test structure 20 in SSC-451

- \( P_p = 3057.1 \text{kN} \)
- \( P_u = 1659.2 \text{kN} \)

- \( P_p \): Full plastic strength
- \( P_u \): Ultimate strength

Model 20
Model 29

$P_p = 1645.1 \text{kN}$

$P_u = 791.0 \text{kN}$

Experiment

$P_u$: Ultimate strength

$P_p$: Full plastic strength

Figure 5.24 Relationship between axial compressive force and axial compressive displacement for test structure 29 in SSC-451
Figure 5.25 Relationship between axial compressive force and axial compressive displacement for test structure 30 in SSC-451

Model 30

P_p = 1645.0 kN
P_u = 908.7 kN

P_u: Ultimate strength
P_p: Full plastic strength

Displacement (mm)

Force (kN)
Figure 5.26 Relationship between axial compressive force and axial compressive displacement for test structure 31 in SSC-451
Model 32

$P_p = 2296.6\text{kN}$

$P_u = 1367.3\text{kN}$

Figure 5.27 Relationship between axial compressive force and axial compressive displacement for test structure 32 in SSC-451
6.1 Structural Modeling

The ANSYS (2008) nonlinear finite element method was employed to compute the ultimate strength behavior of the test structures. The following describes the structural modeling technique applied in the present study.

6.1.1 Extent of the Analysis

It is desirable to extend the extent of the analysis to the entire structure under consideration. If the funds available for structural modeling and computation are limited, however, only a part of the target structure may be included in the finite element modeling.

If only a partial structure is involved in the analysis, then it is important to realize that an artificial boundary is often formed for the target structure, and thus it must be modeled as appropriate in conjunction with mathematics and engineering.

Current practices in the maritime industry show that structural modeling with analysis to a partial extent provides reasonable solutions that are good enough for the practical purposes of structural design and strength assessment as long as the boundary conditions among the other factors are idealized in a relevant way.

The analysis of a partial structure usually involves a cut out of the target structure with respect to the symmetric boundary in terms of structural deformations and failure modes. The extent of the analysis should, in fact, be expanded if possible to reflect the boundary conditions of the target structure more realistically.

Figure 6.1 presents some examples that show the extent of the analysis for the plates and stiffened plate structures. In SSC-451, the two-bay plate-stiffener combination model shown in Figure 6.1(c) was employed to save computational efforts on the 78 test structures.

Figure 6.1(a) A quarter model for a rectangular plate under uniaxial compression
Figure 6.1(b) A one-bay plate-stiffener combination model for a stiffened plate structure under uniaxial compression

Figure 6.1(c) A two-bay plate-stiffener combination model for a stiffened plate structure under uniaxial compression

Figure 6.1(d) A one-bay stiffened panel model for a stiffened plate structure under uniaxial compression
In the present study, the three-bay stiffened panel model shown in Figure 6.1(f) was employed, although the target structure is the plate panel in the middle. This model was adopted because it was able to reflect the nonlinear behavior of the entire stiffened plate structure more realistically. However, transverse frames were not included in the structural modeling, although the support condition at the transverse frames was modeled as appropriate, as will be described in Section 6.1.7.

6.1.2 Types of Finite Elements

A variety of finite element types are available in practice, but it is difficult to establish specific guidelines about which types of finite elements are the best to apply. For the nonlinear analysis of thin-walled or plated structures, however, current practice indicates that the rectangular type of plate-shell elements is more appropriate than the triangular type, because this type more easily defines the membrane stress components inside each element when the Cartesian coordinate system is applied.

For the nonlinear analysis of ships and offshore structures, in association with ultimate limit states and structural crashworthiness, therefore, four-node plate-shell elements are more often employed, in which the nodal points in the plate thickness direction are located in the mid-thickness of each element, thus indicating that no
element mesh is assigned to the thickness layers.

To reflect nonlinear behavior more accurately, the use of plate-shell elements is desirable in the modeling of support members, including both webs and flanges as well as plate parts, although beam elements are sometimes more efficient for modeling these members or at least the flanges.

In the present study, four-node plate-shell elements were employed for the structural modeling. The stiffener web and flange and the plating were all modeled using four-node plate-shell elements.

Figure 6.2 represents a view of the finite element models of all the test structures at the y-z plane. It is noted that the sectional profile of extruded stiffener web has non-uniform wall thickness as shown in Figure 3.9 of Chapter 3, and thus it is modeled by multiple elements with a uniform-thickness per each element as shown in Figure 6.2. Also, a single element is allocated for the softened zone of the stiffener web as of the plate part.
Model 18D

Figure 6.2(d) A view of the finite element model of test structure 18D in the y-z plane

Model 19D1

Figure 6.2(e) A view of the finite element model of test structure 19D1 in the y-z plane

Model 19D2

Figure 6.2(f) A view of the finite element model of test structure 19D2 in the y-z plane

Model 20D1

Figure 6.2(g) A view of the finite element model of test structure 20D1 in the y-z plane
6.1.3 Size of the Finite Elements

Although finer mesh modeling certainly results in more accurate solutions, it is not necessarily the best practice. A similar degree of accuracy can actually be attained with coarser mesh modeling, which requires less computational cost.

A convergence study is usually required to determine the ‘best size’ for the finite element mesh by balancing computational cost with the resulting accuracy. In such a study, sample applications of the corresponding nonlinear analysis are made by varying the element mesh size and searching for the largest finite element size that provides a sufficient level of accuracy.

Although a convergence study is often able to provide best practice for nonlinear finite element modeling in terms of a determination of the relevant mesh size, such a study itself sometimes requires a lot of computational effort. Therefore, useful guidance is necessary to define the finite element mesh size without a convergence study.
Current practice for the ultimate strength analysis of stiffened plate structures that involve an elastic-plastic large deflection response indicates that at least eight four-node plate-shell elements are required to model the plating in between the small support members (e.g., the longitudinal stiffeners). The size of these plate-shell elements is assigned in the plate length direction so that the aspect ratio of each finite element is almost unity, which is desirable. The number of stiffener webs in the web height direction may be more than six using four-node plate-shell elements, and the number of stiffener flanges in the flange breadth direction may be at least two.

In the present study, a total of 16 four-node plate-shell elements were allocated for the plating between the longitudinal stiffeners in the transverse direction. For the stiffener web, a total of eight four-node plate-shell elements were assigned in the stiffener height direction for test structures 20D1 and 20D2, which had a deeper web height. For the remaining test structures, a total of six elements were employed. The stiffener flanges were modeled using four plate-shell elements, i.e., there were two elements on each side of the flanges with respect to the center line. Figure 6.2 also represents the size of the finite elements for the test structures.

As also discussed in Section 6.1.6, non-continuity or a sharp change in the material properties and residual stresses occurs around the softened zone. This may cause additional nonlinearity, and therefore a finer set of finite elements may need to be assigned in this region. However, it has been found that the finite element method model with a single element in the softened zone in the transverse (panel-breadth) direction gives sufficiently good computations within 0.5% deviations in terms of the ultimate strength behavior. Thus, the present study assigned a single element in the softened zone for the nonlinear finite element method computations.

6.1.4 Material Models - Base Material and Softened Zone

The ultimate strength behavior of structures almost always involves material nonlinearity in association with plasticity or yielding, among other factors. For nonlinear finite element analysis, therefore, the characteristics of material behavior should be modeled as appropriate in terms of the stress versus strain relationship.

It is, of course, desirable to employ a realistic relationship between the stresses and strains of the materials that is obtained by a direct test program that covers pre-yielding behavior, yielding, post-yielding behavior, including the strain-hardening effect, ultimate strength, and post-ultimate strength behavior, including the necking effect. This is particularly important for the analysis of structural crashworthiness made necessary by accidental events.

In the present study, the stress-strain curves of the base materials used for the test structures were obtained by tensile coupon tests, as described in Chapter 3. These data were used directly for the finite element analyses presented here, i.e., the entire history of the stress-strain relationship, including the strain-hardening effect, is considered.

However, it was not possible to obtain test results for the stress-strain curves of the materials in the softened zone, although their reduced yield strength was approximately defined, as described in Chapter 4. For the finite element method computations presented here, therefore, the material model illustrated in Figure 6.3
was applied to the materials in the softened zone. In this model, the post-yield behavior of these materials was considered to be similar to that of the base material, whereas the elastic modulus remained unchanged and the yield strength was reduced.

![Diagram of stress-strain relationship](image)

**Figure 6.3 A material model for materials in the softened zone in terms of the relationship between the stress ($\sigma$) and the strain ($\varepsilon$)**

### 6.1.5 Conditions at the Boundaries and Supports

Figure 6.4 shows the nonlinear finite element model applied to compute the ultimate strength behavior of the test structures.

The boundary and support conditions applied in the numerical computations are as follows.

- **Loaded edges (AB, GH):** These remain straight in both the $x$ and $z$ directions over their entirety, including the plate part and the extruded stiffeners. The extruded stiffeners remain upright in both the $x$ and $y$ directions, although they are able to move in parallel in the transverse ($y$) direction. The deformations in the $z$ direction, i.e., the lateral deflections, are unrestrained.

- **Unloaded edges (ACEG, BDFH):** These remain straight in the $y$ direction over their entirety. The deformations in the $z$ direction are unrestrained.

- **Supports at the transverse frames (CD, EF):** The deformations of the plate part in the $z$ direction are restrained. The extruded stiffeners remain upright in the $y$ direction, and may or may not rotate about the $y$ axis, i.e., at the transverse frames in the $x$ direction. For the long and slender stiffeners with a relatively large column slenderness ratio ($\lambda$) value, the transverse frames may keep them upright in both the $x$ and $y$ directions. The extruded stocky-stiffeners with a relatively small column slenderness ratio value, however, are able to rotate in the $x$ direction, but remain upright in the $y$ direction. Test structures 17D and 18D, which have a column...
slenderness ratio greater than 0.9, are modeled such that the extruded stiffeners at the transverse frames keep them upright in both the x and y directions. For the remainder of the test structures, the extruded stiffeners at the transverse frames are able to rotate about the y axis, although they remain upright in the y direction. To resolve this issue more satisfactorily, it is desirable to include the transverse frames themselves in the finite element modeling, but allow the rotational degree of freedom associated with the upright condition of the stiffeners at the transverse frames in both the x and y directions. Further studies are recommended in this regard.

Figure 6.4 Nonlinear finite element model for the test structures

6.1.6 Loading Condition

Longitudinal axial compressive actions are applied via the nodal points at the two loaded edges, thus generating uniformly distributed axial compressive stresses in the x direction.

6.1.7 Initial Distortions

Three types of initial distortions, namely, plate initial deflection, the column-type initial distortion of the stiffener, and the sideways initial distortion of the stiffener are considered here. For plate initial deflection, the maximum value of the initial deflection on the three plates of each test structure is taken as the reference initial
deflection value \( w_{\text{opl}}^* \), and the shape of the initial deflection for each plate is assumed to be as follows.

\[
w_{\text{opl}} = w_{\text{opl}}^* \sin \frac{m \pi x}{a} \sin \frac{\pi y}{b},
\]

(6.1)

where \( m \) is the buckling half-wave number of the plate, which is taken as 4 for the test structures.

The maximum value of the column-type initial distortions on the four stiffeners of each test structure is taken as the reference initial distortion value \( w_{\text{oc}}^* \), and the shape of the initial distortion for the entire plate panel is assumed to be as follows.

\[
w_{\text{oc}} = w_{\text{oc}}^* \sin \frac{\pi x}{a} \sin \frac{\pi y}{b}.
\]

(6.2)

Finally, the maximum value of the sideways initial distortions of the four stiffeners of each test structure is taken as the reference initial distortion value \( w_{\text{os}}^* \), and the shape of the initial distortion for each stiffener is assumed to be as follows.

\[
w_{\text{os}} = w_{\text{os}}^* \frac{z}{h_w} \sin \frac{\pi x}{a},
\]

(6.3)

where \( z \) is the coordinate in the stiffener height direction.

These three types of initial distortions are superimposed on the target structures and allocated in the coordinates via the nodal points, as appropriate.

Directions of column-type initial distortions of stiffeners can govern the stiffened panel collapse patterns and result in the plate-induced failure or stiffener-induced failure. In this regard, two types of the column-type initial distortion direction of stiffeners, i.e., compression in plate (CIP) and compression in stiffener (CIS), are considered in the present finite element method computations.

The CIP type represents the column-type initial distortion of stiffeners in the central panel of the structure in which the plate part is subjected to compression and the stiffener side is subjected to tension. The CIS type indicates an opposite situation to that of the CIP type. Figure 6.5 represents schematics of the abovementioned CIP and CIS types of the column initial distortion of stiffeners, which reflect the conditions at the boundaries and supports as described in Section 6.1.5. While the cross sections of the structure at the loaded edges are kept both plane and upright, the cross sections of the structure at the transverse frames may or may not keep upright, that is, may not or may rotate with regard to the \( y \) axis, although they still remain plane.

As discussed in Section 6.1.5, the nonlinear finite element method computations of test structures 17D and 18D with the slender stiffeners presume the condition in that the cross sections at the transverse frames remain upright.
Figure 6.5(a) The CIP type of the column initial distortion of stiffeners in the central panel of the structure, with the cross sections at the transverse frames rotating with regard to the y axis.

Figure 6.5(b) The CIP type of the column initial distortion of stiffeners in the central panel of the structure, with the cross sections at the transverse frames keeping upright.

Figure 6.5(c) The CIS type of the column initial distortion of stiffeners in the central panel of the structure, with the cross sections at the transverse frames rotating with regard to the y axis.

Figure 6.5(d) The CIP type of the column initial distortion of stiffeners in the central panel of the structure, with the cross sections at the transverse frames keeping upright.
6.1.8 Welding Residual Stresses

Welding residual stresses, which are composed of tensile residual stress blocks and compressive residual stress blocks, were dealt with as initial stresses in the structures. Initial strains, which are possibly caused by heating and cooling down in association with residual stresses, may or may not affect the ultimate strength behavior, but the present study neglects the effects of such strains. Further studies are recommended to consider this issue.

One remaining issue is how to allocate the number of finite elements in the region of the tensile residual stress blocks that corresponds to the softened zone. This is important, because non-continuity or a sharp change in the residual stress distribution occurs around this zone. However, it was found that a single finite element in the softened zone was sufficient for the nonlinear finite element method computations, as described in Section 6.2. This finding is also available for steel-plated structures (Paik & Sohn 2009).

In the present study, the idealized distributions of the residual stresses described in Chapter 4 were applied for the numerical computations.

6.2 Computational Results and Discussions

Figures 6.6 to 6.15 show the relationships between the axial compressive force and the axial compressive displacement of the test structures. The results of the CIS computations indicate an opposite condition to those of the CIP, that is, the stiffener flange side is subjected to compression while the plate side is subjected to tension. These computations were also carried out both with and without residual stresses and softening effects.

Tables 6.1 and 6.2 summarize the ultimate compressive strength computations by a comparison with experimental results. In Table 6.2, the ultimate compressive forces $P_u$ obtained by FEA indicates a smaller value of the ultimate compressive forces computed by either CIP or CIS with the residual stress and softening effects. The ultimate strength ratio to the fully plastic force indicates the severity of local failures in the structures until the ultimate strength reached. In other words, the ultimate strength ratio becomes smaller as the local failures occur earlier and/or more severely. In general, more stocky structures will have a larger value of the ultimate strength ratio or more slender structures will have a smaller value of the ultimate strength ratio. This is because the stocky structures may buckle involving a certain degree of plasticity although the slender structures may buckle in the elastic regime.

It is found from Figures 6.6 to 6.15 that the residual stresses and softening phenomena significantly reduce the ultimate strength performance. The nonlinear finite element method computations for both the CIP and CIS column-type initial distortions of the stiffeners taking into account the effects of residual stresses and softening provide good agreement with the experimental results, except for structures 20D1 and 20C, which unintentionally collapsed earlier through delamination in the friction stir-welded region rather than via buckling collapse. However, it is important to realize that the nonlinear finite element method computations depend significantly on the structural modeling techniques applied.
Table 6.1 Summary of the ultimate compressive strength computations for the test structures in terms of the ultimate compressive stress normalized by the equivalent yield stress

<table>
<thead>
<tr>
<th>Model (Fig. No.)</th>
<th>Experiment</th>
<th>FEA</th>
<th>Without residual stress and softening</th>
<th>With residual stress and softening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>CIP</td>
<td>CIS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CIP</td>
<td>CIS</td>
</tr>
<tr>
<td>$\sigma_{xu}/\sigma_{Ye}$</td>
<td>Collapse mode</td>
<td>$\sigma_{xu}/\sigma_{Ye}$</td>
<td>$\sigma_{xu}/\sigma_{Ye}$</td>
<td>$\sigma_{xu}/\sigma_{Ye}$</td>
</tr>
<tr>
<td>19A (6.6)</td>
<td>0.429</td>
<td>V</td>
<td>0.514</td>
<td>0.512</td>
</tr>
<tr>
<td>20A (6.7)</td>
<td>0.649</td>
<td>IV</td>
<td>0.759</td>
<td>0.745</td>
</tr>
<tr>
<td>17D (6.8)</td>
<td>0.512</td>
<td>III</td>
<td>0.616</td>
<td>0.609</td>
</tr>
<tr>
<td>18D (6.9)</td>
<td>0.531</td>
<td>III</td>
<td>0.649</td>
<td>0.649</td>
</tr>
<tr>
<td>19D1 (6.10)</td>
<td>0.545</td>
<td>III</td>
<td>0.572</td>
<td>0.569</td>
</tr>
<tr>
<td>19D2 (6.11)</td>
<td>0.504</td>
<td>V</td>
<td>0.591</td>
<td>0.588</td>
</tr>
<tr>
<td>20D1 (6.12)</td>
<td>0.511</td>
<td>IV</td>
<td>0.837</td>
<td>0.835</td>
</tr>
<tr>
<td>20D2 (6.13)</td>
<td>0.673</td>
<td>IV</td>
<td>0.837</td>
<td>0.823</td>
</tr>
<tr>
<td>19C (6.14)</td>
<td>0.571</td>
<td>II</td>
<td>0.612</td>
<td>0.621</td>
</tr>
<tr>
<td>20C (6.15)</td>
<td>0.577</td>
<td>IV</td>
<td>0.780</td>
<td>0.777</td>
</tr>
</tbody>
</table>

Note: 1) Test structure that unintentionally collapsed through delamination in the friction stir-welded region; Collapse mode is as defined in Section 5.1; CIP = column-type initial distortion of the stiffeners in the x direction with compression on the plate side; CIS = column-type initial distortion of the stiffeners in the x direction with compression on the stiffener side; $\sigma_{xu} = P_u / A_t$ where $A_t$ = total cross-sectional area of the entire stiffened panel.
Table 6.2 Summary of the ultimate compressive strength computations for the test structures in terms of the ultimate compressive force normalized by the fully plastic force

<table>
<thead>
<tr>
<th>Model (Fig. No.)</th>
<th>( P_p ) (kN)</th>
<th>Experiment</th>
<th>FEA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( P_u ) (kN)</td>
<td>( P_u/P_p )</td>
<td>( P_u ) (kN)</td>
</tr>
<tr>
<td>19A (6.6)</td>
<td>1646.9</td>
<td>0.423</td>
<td>715.4</td>
</tr>
<tr>
<td>20A (6.7)</td>
<td>2139.7</td>
<td>0.655</td>
<td>1382.9</td>
</tr>
<tr>
<td>17D (6.8)</td>
<td>2009.4</td>
<td>0.501</td>
<td>1053.2</td>
</tr>
<tr>
<td>18D (6.9)</td>
<td>2003.8</td>
<td>0.517</td>
<td>1152.5</td>
</tr>
<tr>
<td>19D1 (6.10)</td>
<td>2095.5</td>
<td>0.531</td>
<td>1109.1</td>
</tr>
<tr>
<td>19D2 (6.11)</td>
<td>1847.8</td>
<td>0.509</td>
<td>987.2</td>
</tr>
<tr>
<td>20D1(^1) (6.12)</td>
<td>3161.6</td>
<td>0.495</td>
<td>2382.1</td>
</tr>
<tr>
<td>20D2 (6.13)</td>
<td>2299.8</td>
<td>0.679</td>
<td>1700.3</td>
</tr>
<tr>
<td>19C (6.14)</td>
<td>1583.5</td>
<td>0.495</td>
<td>821.5</td>
</tr>
<tr>
<td>20C(^1) (6.15)</td>
<td>1999.1</td>
<td>0.583</td>
<td>1517.3</td>
</tr>
</tbody>
</table>

Note: \(^1\) Test structure that unintentionally collapsed through delamination in the friction stir-welded region; Collapse mode is as defined in Section 5.1; \( P_u \) = ultimate compressive force; \( P_p \) = fully plastic axial force; \( \sigma_{xu} = P_u / A_t \) where \( A_t \) = total cross-sectional area of the entire stiffened panel.
Figure 6.6 The axial compressive force versus the axial compressive displacement of test structure 19A
Figure 6.7 The axial compressive force versus the axial compressive displacement of test structure 20A
Model 17D

Figure 6.8 The axial compressive force versus the axial compressive displacement of test structure 17D

1: CIP without residual stress and softening
2: CIS without residual stress and softening
3: CIP with residual stress and softening
4: CIS with residual stress and softening
5: Experiment

$P_p = 2009.4 \text{kN}$
Figure 6.9 The axial compressive force versus the axial compressive displacement of test structure 18D
Figure 6.10 The axial compressive force versus the axial compressive displacement of test structure 19D1
Figure 6.11 The axial compressive force versus the axial compressive displacement of test structure 19D2

Model 19D2

P_p = 1847.8 kN

1: CIP without residual stress and softening
2: CIS without residual stress and softening
3: CIP with residual stress and softening
4: CIS with residual stress and softening
5: Experiment
Figure 6.12 The axial compressive force versus the axial compressive displacement of test structure 20D1

1: CIP without residual stress and softening
2: CIS without residual stress and softening
3: CIP with residual stress and softening
4: CIS with residual stress and softening
5: Experiment

Model 20D1

$P_p = 3161.6\text{kN}$
Figure 6.13 The axial compressive force versus the axial compressive displacement of test structure 20D2.

Model 20D2

$P_p = 2299.8 \text{kN}$

1: CIP without residual stress and softening
2: CIS without residual stress and softening
3: CIP with residual stress and softening
4: CIS with residual stress and softening
5: Experiment
Figure 6.14 The axial compressive force versus the axial compressive displacement of test structure 19C

1: CIP without residual stress and softening
2: CIS without residual stress and softening
3: CIP with residual stress and softening
4: CIS with residual stress and softening
5: Experiment
Figure 6.15 The axial compressive force versus the axial compressive displacement of test structure 20C.
6.3 SSC-451 Database

Figures 6.15 to 6.26 show the relationships between the axial compressive force versus the axial compressive displacement of the test structures studied in SSC-451 via fusion welds. Tables 6.3 and 6.4 present a summary of the ultimate strength computations for these structures. It is found that the nonlinear finite element computations for all the test structures are comparable with the experimental results. This implies that the SSC-451 test structures collapsed intentionally via buckling collapse unlike the present test structures in which two structures collapsed unintentionally by delamination before the ultimate strength had been reached.

This database is utilized for a comparison of the ultimate strength performance of fusion welds versus that of friction stir welds, which is described in Chapter 7.

![Model 5](image)

Figure 6.16 The axial compressive force versus the axial compressive displacement of test structure 5
Figure 6.17 The axial compressive force versus the axial compressive displacement of test structure 6
Figure 6.18 The axial compressive force versus the axial compressive displacement of test structure 7.
Figure 6.19 The axial compressive force versus the axial compressive displacement of test structure 8

Model 8

Pu=1513.75kN
Pp=2482.8kN

1: CIP with residual stress and softening
2: CIS with residual stress and softening
3: Experiment
Figure 6.20 The axial compressive force versus the axial compressive displacement of test structure 17
Figure 6.21 The axial compressive force versus the axial compressive displacement of test structure 18
Figure 6.22 The axial compressive force versus the axial compressive displacement of test structure 19
Figure 6.23 The axial compressive force versus the axial compressive displacement of test structure 20
Figure 6.24 The axial compressive force versus the axial compressive displacement of test structure 29.
Model 30

$P_p = 1645.0\text{kN}$

1: CIP with residual stress and softening
2: CIS with residual stress and softening
3: Experiment

Figure 6.25 The axial compressive force versus the axial compressive displacement of test structure 30
Figure 6.26 The axial compressive force versus the axial compressive displacement of test structure 31
Figure 6.27 The axial compressive force versus the axial compressive displacement of test structure 32

Model 32

\[ P_p = 2296.6 \text{kN} \]
Table 6.3 Summary of the ultimate compressive strength computations for the SSC-451 test structures in terms of the ultimate compressive stress normalized the equivalent yield stress

<table>
<thead>
<tr>
<th>Model (Fig. No.)</th>
<th>Experiment</th>
<th>FEA</th>
<th>With residual stress and softening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CIP</td>
<td>CIS</td>
</tr>
<tr>
<td></td>
<td>σ_xu/σ_yeq</td>
<td>Collapse mode</td>
<td>σ_xu/σ_yeq</td>
</tr>
<tr>
<td>5 (6.16)</td>
<td>0.448</td>
<td>III</td>
<td>0.478</td>
</tr>
<tr>
<td>6 (6.17)</td>
<td>0.530</td>
<td>III</td>
<td>0.516</td>
</tr>
<tr>
<td>7 (6.18)</td>
<td>0.516</td>
<td>III</td>
<td>0.554</td>
</tr>
<tr>
<td>8 (6.19)</td>
<td>0.615</td>
<td>V</td>
<td>0.604</td>
</tr>
<tr>
<td>17 (6.20)</td>
<td>0.431</td>
<td>III</td>
<td>0.506</td>
</tr>
<tr>
<td>18 (6.21)</td>
<td>0.460</td>
<td>III</td>
<td>0.532</td>
</tr>
<tr>
<td>19 (6.22)</td>
<td>0.513</td>
<td>III, IV</td>
<td>0.602</td>
</tr>
<tr>
<td>20 (6.23)</td>
<td>0.627</td>
<td>III, IV</td>
<td>0.575</td>
</tr>
<tr>
<td>29 (6.24)</td>
<td>0.447</td>
<td>V</td>
<td>0.486</td>
</tr>
<tr>
<td>30 (6.25)</td>
<td>0.515</td>
<td>V</td>
<td>0.532</td>
</tr>
<tr>
<td>31 (6.26)</td>
<td>0.494</td>
<td>III, IV</td>
<td>0.564</td>
</tr>
<tr>
<td>32 (6.27)</td>
<td>0.548</td>
<td>III, IV</td>
<td>0.608</td>
</tr>
</tbody>
</table>

Note: Collapse mode is as defined in Section 5.1; CIP = column-type initial distortion of the stiffeners in the x direction with compression on the plate side; CIS = column-type initial distortion of the stiffeners in the x direction with compression on the stiffener side; \( \sigma_{xu} = \frac{P_u}{A_t} \) where \( A_t \) = total cross-sectional area of the entire stiffened panel.
Table 6.4 Summary of the ultimate strength computations for the SSC-451 test structures in terms of the ultimate force normalized by the fully plastic force

<table>
<thead>
<tr>
<th>Model (Fig. No.)</th>
<th>$P_p$ (kN)</th>
<th>Experiment</th>
<th>FEA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$P_u$ (kN)</td>
<td>$P_u/P_p$</td>
</tr>
<tr>
<td>5 (6.16)</td>
<td>1831.3</td>
<td>777.8</td>
<td>0.425</td>
</tr>
<tr>
<td>6 (6.17)</td>
<td>1831.2</td>
<td>918.0</td>
<td>0.501</td>
</tr>
<tr>
<td>7 (6.18)</td>
<td>1903.4</td>
<td>931.8</td>
<td>0.490</td>
</tr>
<tr>
<td>8 (6.19)</td>
<td>2482.8</td>
<td>1513.8</td>
<td>0.610</td>
</tr>
<tr>
<td>17 (6.20)</td>
<td>2049.0</td>
<td>778.0</td>
<td>0.380</td>
</tr>
<tr>
<td>18 (6.21)</td>
<td>2048.8</td>
<td>829.6</td>
<td>0.405</td>
</tr>
<tr>
<td>19 (6.22)</td>
<td>2160.5</td>
<td>970.5</td>
<td>0.449</td>
</tr>
<tr>
<td>20 (6.23)</td>
<td>3057.1</td>
<td>1659.2</td>
<td>0.543</td>
</tr>
<tr>
<td>29 (6.24)</td>
<td>1645.1</td>
<td>791.0</td>
<td>0.481</td>
</tr>
<tr>
<td>30 (6.25)</td>
<td>1645.0</td>
<td>908.7</td>
<td>0.552</td>
</tr>
<tr>
<td>31 (6.26)</td>
<td>1717.2</td>
<td>895.9</td>
<td>0.522</td>
</tr>
<tr>
<td>32 (6.27)</td>
<td>2296.6</td>
<td>1367.3</td>
<td>0.595</td>
</tr>
</tbody>
</table>

Note: $P_u$ = ultimate compressive force; $P_p$ = fully plastic axial force.
Chapter 7 Comparison of Ultimate Compressive Strength Performance between Fusion Welds and Friction Stir Welds

7.1 Ultimate Compressive Strength Design Formulae for Fusion-welded Structures

When a continuous stiffened plate structure is modeled as an assembly of plate-stiffener combinations, it is recognized that the ultimate compressive strength of the representative plate-stiffener combination model can be given by the following equation (Paik & Thayamballi 2003).

$$\frac{\sigma_{ux}}{\sigma_{yeq}} = \frac{1}{\sqrt{C_1 + C_2 \lambda^2 + C_3 \beta^2 + C_4 \lambda^2 \beta^2 + C_5 \lambda^4}},$$

(7.1)

where $C_1$ - $C_5$ = the coefficients to be determined from a database, $\sigma_{yeq}$ = equivalent yield strength calculated from the average yield strength as described in Section 3.2.2.

The ultimate strength, $\sigma_{ux}$, computed from Equation (7.1) should be smaller than the elastic buckling strength as a column, namely

$$\frac{\sigma_{ux}}{\sigma_{yeq}} \leq \frac{1}{\lambda^2}.$$  

(7.2)

For welded steel stiffened plate structures, the following coefficients for Equation (7.1) have been suggested (Paik & Thayamballi 2003).

$$C_1 = 0.995, \quad C_2 = 0.963, \quad C_3 = 0.170, \quad C_4 = 0.188, \quad \text{and} \quad C_5 = -0.067.$$  

(7.3)

The coefficients of Equation (7.1) for fusion fillet-welded aluminum stiffened plate structures were determined based on the SSC-451 database, depending on the type of stiffener, as follows (Paik 2007, Paik et al. 2008a).

• Tee or angle type (extruded or built-up):

$$C_1 = 1.318, \quad C_2 = 2.759, \quad C_3 = 0.185, \quad C_4 = -0.177, \quad \text{and} \quad C_5 = 1.003.$$  

(7.4)

• Flat bar type:

$$C_1 = 2.50, \quad C_2 = -0.588, \quad C_3 = 0.084, \quad C_4 = 0.069, \quad \text{and} \quad C_5 = 1.217.$$  

(7.5)

For fusion-welded aluminum stiffened plate structures with flat bar-type stiffeners, the ultimate compressive strength, $\sigma_{ux}$, computed from Equation (7.1), together with the coefficients of Equation (7.5), should be smaller than the following value and the elastic buckling stress defined in Equation (7.2), that is,
\[ \frac{\sigma_{xu}}{\sigma_{Yeq}} \leq \frac{1}{\sqrt{-16.297 + 18.776\lambda + 17.716\beta - 22.507\lambda\beta}} \cdot (7.6) \]

7.2 5083 Plates with \( \beta = 2.45-2.86 \)

Figure 7.1 provides a comparison between the ultimate strength performance of fusion welds and friction stir welds for the test structures in which the plate part is made of 5083 alloys. Plate slenderness ratio \( \beta \) is in the range of 2.45 to 2.86, and the variation in the ultimate strength performance is represented as a function of column slenderness ratio \( \lambda \), which is computed as a representative plate-stiffener combination, i.e., for a single stiffener with attached plating.

The shaded region in Figure 7.1 indicates the ultimate strength of friction stir-welded test structures. The ultimate strength design formula solutions using Equation (7.1), together with the coefficients of Equation (7.4), are also compared.

It should be noted that test structure 20D-1, which was fabricated via friction stir-welded lap-joining, reached its ultimate strength unintentionally through delamination in the welded region rather than via buckling collapse.

It is evident from Figure 7.1 together with Tables 5.1, 5.2 and 6.1 to 6.4 that the ultimate strength performance of friction stir-welded aluminum structures is superior to that of fusion-welded aluminum structures. It is observed that the use of friction stir welds can increase the ultimate strength performance by 10-20% compared to fusion welds, as long as the quality of the friction stir-welded region is assured.

7.3 5383 Plates with \( \beta = 2.66-2.72 \)

A similar comparison of the ultimate strength performance of fusion and friction stir welds for 5083 alloy plates is shown in Figure 7.2 for the test structures in which the plate part is made of 5383 alloys. Plate slenderness ratio \( \beta \) is in the range of 2.66 to 2.72, and the ultimate strength design formula solutions using Equation (7.1), together with the coefficients of Equation (7.4), are also compared. The shaded region in Figure 7.2 indicates the ultimate strength of friction stir-welded test structures.

It should be noted that test structure 20C, which was fabricated via friction stir-welded butt-joining, reached its ultimate strength unintentionally through delamination in the welded region rather than via buckling collapse. It is evident that a similar conclusion to that for the 5083 plates is reached for the friction stir-welded aluminum structures with 5383 alloy plates.
Figure 7.1 Variation in the ultimate compressive strength performance of fusion-welded and friction stir-welded aluminum stiffened plate structures with 5083 alloy plates.
7.4 Ultimate Compressive Strength Design Formula for Friction Stir-welded Structures

The number of test data points valid for the anticipated buckling collapse mode of friction stir-welded structures is six, while the results of test structures 20D1 and 20C which had reached the ultimate limit state by an unintended collapse mode due to delamination in the friction stir-welded region are excluded.

Due to the limited amount of test data points, it is not straightforward to develop
ultimate strength design formula for friction stir-welded structures. Nevertheless, the present study attempts to determine the coefficients $C_1$ through $C_5$ of Equation (7.1) applying direct optimization and least square techniques as follows.

$$C_1 = 0.2870, \quad C_2 = 0.0, \quad C_3 = 0.2096, \quad C_4 = 0.4937, \text{ and } C_5 = -0.6790. \quad (7.7)$$

In terms of implementing the coefficients of Equation (7.7) into Equation (7.1), Equation (7.2) is applied. Also, the coefficients of Equation (7.7) are found to be valid for the column slenderness ratio smaller than 1.4. Figure 7.3 presents the accuracy of Equation (7.1) together with Equation (7.7) by a comparison with experimental results. It is seen from Figure 7.3 that the solutions of the ultimate strength design formula, i.e., Equation (7.1) with the coefficients of Equation (7.7), are in reasonably good agreement with the test data points of the friction stir-welded aluminum structures.

![Figure 7.3 Accuracy of the ultimate compressive strength design formula for friction stir-welded aluminum structures](image-url)
Chapter 8 Conclusions and Recommendations

The objectives of this study were to develop a mechanical buckling collapse test database for 5000’s and 6000’s series aluminum stiffened plate structures fabricated by friction stir welding and to compare these structures with similar aluminum plate panels fabricated by fusion welding in terms of weld-induced initial imperfections and ultimate compressive strength performance.

In SSC-451, the ultimate strength characteristics of 78 aluminum stiffened plate structures fabricated by fusion fillet welding were investigated through buckling collapse tests and the nonlinear finite element method. The statistics for the fusion weld-induced initial imperfections were analyzed in terms of the mean values and standard deviations at three levels, namely, the slight, average, and severe levels. Ultimate compressive strength design formulae were also developed for the fusion-welded aluminum stiffened plate structures based on the database of the buckling collapse tests and nonlinear finite element method computations. A total of 12 test structures in SSC-451 that had extruded stiffeners were selected and utilized for a comparison with a total of 10 test structures in the present study in which 8 test structures were fabricated by friction stir welding (6 lap-welds and 2 butt-welds) and 2 test structures were fabricated by fusion fillet welding.

The trends or benefits found to be associated with the fusion welding and friction stir welding procedures are discussed in Chapters 3 to 7. The following is a summary of these discussions.

Chapter 3 presents the mechanical properties of aluminum alloys in fusion- and friction-stir welded region of butt welds as well as in base (parent) material, which were obtained from tensile coupon tests. It is found that the tensile property in the butt-welded material of friction stir welding is equivalent or even better than that of fusion welding.

Chapter 4 presents the database of weld-induced initial imperfections for the aluminum stiffened plate structures obtained from SSC-451 and the present study, and also provides a comparison of the initial imperfections induced by fusion welds and those induced by friction stir welds. It is concluded that the initial imperfections induced by friction stir welding are smaller than those induced by fusion welding. Thus, the benefits of the friction stir welding procedure in this respect are clear.

Chapter 5 presents the database of the buckling collapse tests on the friction stir-welded aluminum stiffened plate structures. Most of the test structures fabricated by both friction stir and fusion welds (Models 19A and 20A) reached their ultimate strength through the anticipated collapse mode. However, all of the friction stir-welded test structures showed delamination in the welded region after or even before the ultimate strength had been reached. For example, delamination occurred in test structures 20D1 and 20C in the pre-collapse range. In contrast, no crack failure was observed in the fusion-welded region of test structures 19A and 20A as well as in the test structures studied in SSC-451 by fusion welds, before and after the ultimate strength had been reached. This indicates that the fusion-weld procedure is superior to the friction stir-weld procedure in terms of compressive strength performance in the welded region.
Since the pre-collapse delamination can significantly reduce the ultimate compressive strength of the structure, the quality assurance in the friction stir-welded region is highly required to prevent delamination failure. In friction stir lap-welded structures, i.e., joined between base plate and extruded stiffeners, delamination may not be of major concern in terms of the water tightness. However, delamination shall be of great concern in friction stir butt-welded structures, i.e., joined between flange free edges of extrusions because the water tightness is no longer assured after delamination. In this regard, the friction stir lap-welding may be more promising than the friction stir butt-welding to replace the fusion fillet-welding, as long as the delamination is concerned.

It is recognized that the mechanical property and delamination in the friction stir-welded region is significantly affected by the welding parameters such as width and depth of molten metal thin layer, molten temperature, rotating and forwarding speeds, and possible quick cooling, etc. It is thus important to establish optimum parameters of friction stir welding to assure the quality of the welded region and also to prevent any weld defects and delamination. Non-destructive test (NDT) methods can be used for the quality assurance in the friction stir welded region.

Chapter 6 presents a comparison of the nonlinear finite element method computations with the experimental results. It is found that this method is able to compute the ultimate strength behavior of welded aluminum structures with a reasonable degree of accuracy. However, it is important to realize that the computational results depend significantly on the structural modeling techniques applied. Through the comparison of the nonlinear finite element computations with experimental results, it turns out that test structures 20D1 and 20C must have collapsed unintentionally earlier.

Chapter 7 presents a comparison of the ultimate compressive strength performance of fusion fillet welds and friction stir butt- or lap-welds. It is found that this performance is 10-20% greater in the friction stir-welded aluminum structures than it is in the fusion-welded aluminum structures. This implies that the friction stir welding procedure is certainly superior to the fusion welding procedure in terms of ultimate compressive strength performance, as long as the delamination in the friction stir welded region is prevented.

It is considered that there are still a lot of challenging issues to be resolved to apply the friction stir welding technology for marine applications. Further studies are recommended as follows.

- Tensile coupon tests for friction stir lap-welds as well as friction stir butt-welds in terms of the mechanical property characterization,
- Microscopic examination of friction stir lap-welds as well as friction stir butt-welds,
- Additional buckling collapse tests for friction stir butt-welds by fabrication method C-2,
- Additional buckling collapse tests for friction stir lap-welds by fabrication method D with different parameters of friction stir welding process such as width and depth of molten thin layer to evaluate the pre- and post-collapse delamination phenomena and their causes.
References


ABS (2006). Rules for material and welding, Part 2 Aluminum and fiber reinforced plastics, Chapter 5, Appendix 1, Table 2, American Bureau of Shipping, Houston, USA.


DNV (2008). Rules for classification of high speed, light craft and naval surface craft, Part 3, Chapter 3, Section 2, Table B4, Oslo, Norway.


Thomas, W.M., Nicholas, E.D., Needham, J.C., Murch, P., Temple-Smith, P. and Dawes,
Appendix Mechanical Properties of the Materials after Buckling

Figures A.1 to A.10 show the stress-strain relationships of the materials that underwent buckling, as obtained from the tensile coupon tests. These materials were cut out of the test structures after the buckling collapse test, as shown in Figure A.11.

Table A.1 Comparison of the mechanical properties of virgin materials with those of the materials that experienced buckling

<table>
<thead>
<tr>
<th>Material</th>
<th>Model</th>
<th>Elastic modulus (N/mm²)</th>
<th>Yield stress (N/mm²)</th>
<th>Ultimate tensile stress (N/mm²)</th>
<th>Elongation (%)</th>
</tr>
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<tbody>
<tr>
<td>5083-H112</td>
<td>Virgin</td>
<td>69856.8</td>
<td>167.2</td>
<td>307.67</td>
<td>33.09</td>
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<tr>
<td>17D</td>
<td>69691.9</td>
<td>154.7</td>
<td>267.4</td>
<td>24.39</td>
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<tr>
<td>18D</td>
<td>68326.1</td>
<td>140.1</td>
<td>266.5</td>
<td>22.35</td>
<td></td>
</tr>
<tr>
<td>19D1</td>
<td>70202.7</td>
<td>138.3</td>
<td>264.6</td>
<td>23.35</td>
<td></td>
</tr>
<tr>
<td>20D1</td>
<td>68675.5</td>
<td>138.7</td>
<td>267.5</td>
<td>22.94</td>
<td></td>
</tr>
<tr>
<td>19C</td>
<td>69439.5</td>
<td>145.8</td>
<td>271.0</td>
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<tr>
<td>5383-H116</td>
<td>Virgin</td>
<td>70355.3</td>
<td>207.9</td>
<td>342.0</td>
<td>25.85</td>
</tr>
<tr>
<td>19A</td>
<td>70254.6</td>
<td>194.6</td>
<td>307.1</td>
<td>12.67</td>
<td></td>
</tr>
<tr>
<td>20A</td>
<td>70668.7</td>
<td>173.1</td>
<td>296.2</td>
<td>13.97</td>
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<tr>
<td>19D2</td>
<td>70151.5</td>
<td>199.9</td>
<td>316.0</td>
<td>14.63</td>
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<td>173.5</td>
<td>297.1</td>
<td>15.20</td>
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</table>

Table A.1 presents a comparison of the mechanical properties of the materials that experienced buckling with those of virgin materials. All the tensile coupon test specimens of the materials after buckling were cut out in the plate longitudinal direction, although the mechanical properties of virgin materials are their average values in the longitudinal, transverse or diagonal directions as those indicated in Chapter 3.

As can be seen from Table A.1, the mechanical properties of the buckling-
experienced materials are inferior to those of the virgin materials. The yield stress, ultimate tensile stress and elongation of the materials that had undergone buckling are significantly reduced when compared to those of virgin materials, although the elastic modulus remains almost unchanged.

Figure A.1 The stress-strain relationship of material 5383-H116 after buckling in test structure 19A
Figure A.2 The stress-strain relationship of material 5383-H116 after buckling in test structure 20A

Figure A.3 The stress-strain relationship of material 5083-H112 after buckling in test structure 17D
Figure A.4 The stress-strain relationship of material 5083-H112 after buckling in test structure 18D

Figure A.5 The stress-strain relationship of material 5083-H112 after buckling in test structure 19D1
Figure A.6 The stress-strain relationship of material 5383-H116 after buckling in test structure 19D2

Figure A.7 The stress-strain relationship of material 5083-H112 after buckling in test structure 20D1
Figure A.8 The stress-strain relationship of material 5383-H116 after buckling in test structure 20D2

Figure A.9 The stress-strain relationship of material 5083-H112 after buckling in test structure 19C
Figure A.10 The stress-strain relationship of material 5383-H116 after buckling in test structure 20C

Figure A.11 Photo of one of the test structures after the material test specimen had been cut out of the buckling collapsed structure
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