THE ANALYSIS OF CASE STUDIES HELPS TO PREPARATION AND EVALUATION OF HIGH STRENGTH STEEL FATIGUE STRENGTH IMPROVING PROGRAMS FOR POST-WELD TREATMENT METHODS

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Abstract
Numerous researchers conducted work on the fatigue strength improvement of high strength steels welding joint by applying different post-weld treatment on it, in the last decade. These research works based on different approaches to compare the post-weld treated welding joints fatigue strength with the as welded condition or with another post-weld treatment processes. These methods are limitedly applied based on practical experiences, however significantly different results were presented in research studies. To compare the different post-weld treatment fatigue strength improvement results on high strength steels, experimental program should be performed. The aims of this article are summarizing the most relevant information for our experimental work based on analysed case studies, and proposing program setup method for evaluation different post-weld treatment process results.

Keywords: high strength steels, fatigue strength improvement, post-weld treatment, weld geometry improvement, residual stress condition improvement, experimental program

1. Introduction
Fatigue properties of welded structures are today a bottleneck for the introduction of high strength steels in high-performance, lightweight welded structures (Gáspár, 2016; Dobosy, 2017; Mobark, 2020; Sisodia, 2021). This caused by high strength steels increased sensitivity to notches and weld discontinuities and/or defects compared to mild strength steels, which limits the use of high strength steels in fatigue loaded structural components. Based on International Institute of Welding (IIW) recommendation (Hobbacher et al., 2009), there is little or no increase in fatigue strength of welded high-strength steel assemblies in the as-welded condition. Welding introduces geometrical notches and metallurgical modifications which give rise to local stress concentrations, and the thermo-metallurgical treatment of the filler metal and the heat affected zone (HAZ) leads to high residual component stresses or huge distortion values of the assembly (e.g., construction of steel structures or pipelines). Currently, it is necessary to apply post-weld treatment to gain increased fatigue strength when introducing high strength steels in structural applications where fatigue is the cause of failure (Ästrand et al., 2016). There are several methods which are used in industry shown in Figure 1, where the most available ones are
marked with green colour. In the most bottom block of Figure 1 “LTT welding” means Low Transformation Temperature welding whose details can be found in the literature (Harati et al., 2017; Igwemezie et al., 2022).

**Figure 1.** Overview of different weld improvement techniques – top part: weld geometry improvement methods; bottom part: residual stress methods (Leitner et al., 2020)
An overview regarding usage and to some extent, fatigue assessment and the increase of fatigue strength, are given in the IIW guidelines for improvement techniques (Hobbacher et al., 2009; Haagensen et al., 2013).

Research efforts over the last years have been conducted to assess an increase in the fatigue life of high strength steel structural elements, using different post-weld treatment methods in regions where the weld toe is critical. However, applying post-weld treatment in production gives additional costs in terms of treatment process time, equipment, as well as staff. In our days, practical experiences show the weld geometry improvement methods are still more utilized in high strength steel welding construction post-weld treatment rather than residual stress concentration methods. This finding originates more from the characteristics of post-treatment technologies than from the geometrical dimensions of the structures and the effects of the treatments on the integrity of the structures; whilst the post-treatment of welding joint is close correlation with the structural integrity (Koncsik, 2019; Koncsik, 2021) of both the welding joint and the welded structural element. Considering the production cost and quality assurance – in other words technological stability – of post-weld treatment processes, it is reasonable to compare not only the improvement achieved compared with as weld condition than also the different processes are interesting to compare.

The aims of this article are summarizing the most relevant information for our experimental work based on reviewed and analysed case studies, and proposing experimental program setup method for evaluation different post-weld treatment process results.

2. Review of experimental programs

Research studies from last decades were reviewed to analyse the experimental programs of fatigue strength improving post-weld treatment methods. Based on analysed 19 research studies several interesting findings were detected what support to prepare our experimental program proposal for comparing post-weld treatment of high strength steel welding joint. Reviewed research reports applying different post-weld treatment methods on welding joints of high strength steels with different experimental specimens presented in Appendix. 60 investigational specimens were published in reviewed studies and 46 from these are focused on high strength steels welding joint fatigue strength improvement. As review analysis result shows in Table 1, the most of reviewed studies focused on high frequency mechanical impact (HFMI) post-weld treatment. Furthermore, important that the reviewed studies are mainly focused to compare the as-weld condition with one to three applied fatigue strength improvement post-weld treatment methods. None of them is comparing the full range of post-weld treatment of high strength steels welding joint. The reviewed research studies also apply other post-weld treatment methods for high strength steel welding joints fatigue improvement which are not industrialized such level as Table 1 presented methods.

| Table 1. Number of applied post-weld treatment methods in reviewed case studies |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Weld geometry improvement methods | Residual stress methods |
| Burr grinding | Disc grinding | TIG dressing | Hammer peening | Needle peening | Shoot peening | HFMI |
| 2 | N/A | 3 | N/A | N/A | 1 | 37 |
Examples – in other words frequently applied cases – of welded joints suitable according IIW recommendation (Hobbacher, 2009) for weld toe improvement methods are shown in Figure 2. In these cases the improvement of fatigue life is considered only from the viewpoint of weld toe. If there existing further imperfections on the root only the origin of the failure shifted from a weld toe to the root therefor fatigue life of the welding joint cannot significantly be improved by post treatment.

![Figure 2. Examples of joints suitable for improvement (Hobbacher, 2009)](image)

Some of welding joints where root cracking might occur are shown in Figure 3. In these cases, which are similarly frequently applied cases, significant improvement of fatigue strength is obtained if full penetration weld or extra-large throats should be used where possible. Improvement of incomplete root penetration should be verified by fatigue testing or by (finite element) analysis (Hobbacher, 2009).

![Figure 3. Examples of joints improvement of fatigue strength limited by occurrence of the root cracking (Hobbacher, 2009)](image)
In the reviewed and analysed research studies applied different welding specimens can categorized according to Figure 2 and Figure 3 classified welding joint categories. The partial penetration butt welded joint shown in Figure 3 (a) were not investigated in the reviewed studies. Industrial practice also confirms in critical areas the partial penetration butt welded joints are not used in welded construction made from high strength steels because of the base materials have high sensitivity to notches and welding defects. Regarding to the IIW recommendation (Hobbacher, 2009), the research studies analysed and industrial practice, welding specimens’ type could be categorized into 7 categories as shown in Table 2.

**Table 2. Categorization of welding specimens’ type based on analysed case studies**

| Welding specimen type          | Specimen setup |
|-------------------------------|----------------|
| Butt weld                     |                |
| Butt weld with different thickness plate | |
| Longitudinal stiffener        |                |
| Transversal stiffener (cruciform type) | |
| Transversal stiffener (T joint type) | |
| Lap joint                     |                |
| Cover plate                   |                |

Welding specimen type analysis shows that the researchers are focused on fatigue strength improvement of longitudinal and transversal stiffener type welding joint post-weld treatment, as 43 welding specimens from the 60 reviewed ones is welded as longitudinal or transversal stiffener. Table 3 summarizes the welding specimen type analysis based on case studies. The welding specimens’ type
like butt weld with different thickness plate, lap joint and cover plate investigated only in few research studies, behind this fact could be that these types of welding joints are not used in critical areas of fatigue loaded high strength steel welded structures.

Table 3. Number of applied welding specimens’ type in reviewed case studies

| Butt weld | Butt weld with different thickness plate | Longitudinal stiffener | Transversal stiffener (cruciform) | Transversal stiffener (T joint) | Lap joint | Cover plate |
|-----------|----------------------------------------|------------------------|-----------------------------------|--------------------------------|-----------|-------------|
| 9         | 1                                      | 21                     | 11                                | 11                             | 3         | 4           |

Analysed results show that welding specimens welded with fillet weld (FW) is investigated 43 cases what is more than two third parts of all investigated welding specimens reviewed in this paper. Furthermore, important to note that in case of longitudinal or transversal stiffener type welding specimens could also welded by fillet weld (FW) or with butt weld (BW) what is influence the fatigue strength of the welding joint. Weld geometry of welding joint surface is influencing the fatigue strength of the welded structures it is obvious that the risk in multi-layer welding joint that the weld geometry contain notches is much higher than single layer welding technique. Therefore, other key factor what is also influencing the fatigue strength of welding joint is the welding technique in cover layer as single-layer or multi-layer technique. Analysis of case studies shows that the 56 welding specimens are welded in single layer and only 4 cases were applied the multi-layer welding technique. It is interesting result because in heavy and/or thick welded structures made of high strength steels multi-layer cover techniques are commonly used due the limitation of the heat input to ensure the right toughness of the welding joint.

Weld shape imperfections influenced by the weld position also. In case of horizontal flat (PA) position welding is obvious the weld shape could be much better than in horizontal PB or PC position rather than vertical down to up position (PF). The welding position is not given in all analysed cases, however the shape of welding in FW welding joint is look like PB position welding in case of butt weld it looks like PA position welding. The welding process according to ISO 4063 (ISO, 2006) is 135, GMAW process in all reviewed cases.

Welding residual stresses are affected by welding circumstances of like free or limited deformability of the welding specimens during the welding. In welded structures the deformability of the welding joint is limited therefore higher residual stresses rise compared with free deformability welding specimens. In the case of welding the specimens under free deformability condition applying residual stress method post-weld treatment can reach better result than specimens welded under limited deformability condition. It is also not mentioned in any reviewed report that the welding was performing under which condition.

In some cases, the weld toe was removed or grinded before applying post-weld treatment in the welding joint what is also important welding condition parameters influencing the fatigue strength of the welding joint.

Based on reviewed case studies, it was started to prepare an experimental program setup proposal what is suitable to define all important details regarding the post-weld treatment of high strength steel welding joints.
3. Experimental program setup proposals

Based on the review of experimental programs can be found in case studies, influencing parameters of post-weld treatment of high strength steels welding joints were classified into three mains categories as shown in Figure 4. Under welding technology those parameters were classified which are influencing as basic parameters of welding process and base material. Parameters classified into welding specimens’ group which are define the specimen preparation like the type and size of specimens and type of welding joint. Post-weld treatment methods and post-weld treatment parameters are classified into the post-weld treatment group.

![Figure 4. Schematic diagram of experimental program setup](image)

Welding technology parameters, as basic parameters, are the steel grade of the inspected base material, the welding process applied during welding, the position of welding, the welding condition and the welding technique of cover layer. Important parameters under welding condition are those parameters which influenced the fatigue strength of the welded specimens, e.g., weld toe pre-machining, specimens welded under limited deformability condition, automatization level of the applied welding process. Overall, it is advised to use automatization during the welding of specimens because increasing the stability of the weld geometry is important to create same condition in each welded specimen. Butt weld, butt weld with different thickness plate and transversal stiffener could be automatized easier because more specimens can be welded in a row applying run on/out plates between the specimens. Longitudinal stiffener, lap joint and cover plate welding could be automatized only in higher level
meaning robotized or cobot systems, reaching same stability in the welding process. Advised is using constant parameters in the research program planning, under the same welding technology parameters the influence of the welding specimens and/or influence of the post-weld treatment methods fatigue strength improvement could be assessed.

Welding specimen parameters are the welding specimen type (listed in Table 2), size of welding specimens contains the geometry of the specimens, the thickness of the plates and the welding joint type as butt weld (BW) or fillet weld (FW) what also define the edge preparation of the specimens.

Post-weld treatment parameters are the applied post-weld treatment process and the process parameters, where process parameters are defined in IIW recommendation (Haagensen et al.; 2013, Marquis et al., 2016) to each process.

The welding specimen and post-weld treatment are the variable parameters of high strength steel welding joints fatigue strength improvement research programs. Based on the target of the research program, either the welding specimen or the post-weld treatment or simultaneously both parameters could be modified. In case of varying post-weld treatment parameters in fixed welding specimens; parameters the different treatment, costs and fatigue improvement result could be optimized. By modifying the welding specimen’s parameters under same post-weld treatment circumstances, the selected methods optimum usage could be assessed from construction design point of view.

For better visualization of experimental program setup, welding specimen – post-weld treatment matrix was prepared for the most industrialized post treatment methods. Under predefined welding technology parameters proposed welding specimen post-weld treatment matrix could be used to plan the welding program based on the target of the program such us complete analysis of the treatment methods or comparing the methods in selected welding specimen type and techniques. For better visualization, the matrix also contains the cover layer welding techniques, as multi-layer (ml) or single-layer (sl) welding. In critical areas, for example after construction damages, both weld specimen and post-weld treatment process parameters could be optimized to find solution by parallelly modifying design of welded construction and select the appropriate post-weld treatment method or parameter.

Considered the welding specimens and post-weld treatment parameters are variable parameters in most cases of research programs it is obvious idea to prepare a 2D matrix linked to the weld specimens – post-weld treatment as variables. This proposed welding specimens – post-weld treatment matrix could be utilized in research program planning and visualization of mapping of results. Consider that the cover layer welding techniques as multi-layer or single-layer has significant influence on fatigue strength of the welding joint therefore our proposal to add the welding techniques also as variable parameter to the welding specimen – post-weld treatment matrix. Based on the above-mentioned considerations, the proposed matrix format is presented in Table 4.

Based on the analysed research studies, the welding specimen – post-weld treatment matrix was completed and presented in Table 4, visualizing the coverage of the welding specimens and post-weld treatment methods. However, it is important to note that the reviewed case studies are not made under same weld technology parameters (like base material, welding condition), and welding specimen size therefore the presented matrix can be used only to show functioning of the welding specimen – post-weld treatment matrix.
Table 4. Welding specimen – post-weld treatment matrix covered by analysed case studies

| Welding specimen type                  | Welding joint type | Welding technique (cover laya) | Burr Grinding | Disc Grinding | TIG Dressing | Hammer Peening | Needle Peening | Shoot Peening | HFMI | LTT welding |
|----------------------------------------|-------------------|--------------------------------|---------------|---------------|--------------|----------------|----------------|--------------|------|-------------|
| Butt weld                              | BW                | sl                             |               |               |              |                |                |              |      |             |
|                                        |                   | ml                             |               |               |              |                |                |              |      |             |
| Butt weld with different plate thickness| BW                | sl                             |               |               |              |                |                |              |      |             |
|                                        |                   | ml                             |               |               |              |                |                |              |      |             |
| Longitudinal stiffeners                | FW                | sl                             |               |               |              |                |                |              |      |             |
|                                        |                   | ml                             |               |               |              |                |                |              |      |             |
|                                        | BW                | sl                             |               |               |              |                |                |              |      |             |
|                                        |                   | ml                             |               |               |              |                |                |              |      |             |
| Transverse stiffeners (cruciform type) | FW                | sl                             |               |               |              |                |                |              |      |             |
|                                        |                   | ml                             |               |               |              |                |                |              |      |             |
|                                        | BW                | sl                             |               |               |              |                |                |              |      |             |
|                                        |                   | ml                             |               |               |              |                |                |              |      |             |
| Transverse stiffeners (T joint type)   | FW                | sl                             |               |               |              |                |                |              |      |             |
|                                        |                   | ml                             |               |               |              |                |                |              |      |             |
|                                        | BW                | sl                             |               |               |              |                |                |              |      |             |
|                                        |                   | ml                             |               |               |              |                |                |              |      |             |
| Lap joint                              | FW                | sl                             |               |               |              |                |                |              |      |             |
|                                        |                   | ml                             |               |               |              |                |                |              |      |             |
| Cover plate                            | FW                | sl                             |               |               |              |                |                |              |      |             |
|                                        |                   | ml                             |               |               |              |                |                |              |      |             |

4. Conclusions

Based on the analysed nineteen research studies and sixty experimental specimens, the following conclusions can be drawn.

The case studies consist essential and applicable information belonging to both the preparation and the evaluation phases of our research program.

The experimental program setup parameters of high strength steels welding joint fatigue strength improvement methods can be classified into three groups, as follows: weld technology, welding specimens and post-weld treatment methods.
In developed and presented methodology, the welding technology parameters are functioning as basic parameters of the experimental program, and weld specimens, post-weld treatment methods are visualized in the weld specimen – post-weld treatment matrix.

This proposed methodology can be used planning the experimental research program to cover the whole type of welding specimens or to compare all most industrialized post-weld treatment methods fatigue strength improvement results. It is important to note, that the sizes of the welding specimens must be also considered to influence to the fatigue strength. Therefore, further analysis should be performed focusing on the size effect.

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APPENDIX
Reviewed case studies experimental program
(BW = butt weld, FW = fillet weld and sl = single-layer, ml = multi-layer)

| No. | Reference                      | Steel grade | Plate thickness 1 | Plate thickness 2 | Welding specimen type                       | Welding joint type | Welding technique (cover layer) | Post-weld treatment |
|-----|--------------------------------|-------------|------------------|------------------|---------------------------------------------|--------------------|---------------------------------|-------------------|
| 1   | Abdulah et al., 2012           | 1.4031      | 5                | 5                | Butt weld                                   | BW                 | sl                             | HFMI              |
| 2   | Aldén et al., 2020             | S700 MC     | 10               | 6                | Transverse stiffener (cruciform type)       | FW                 | sl                             | HFMI              |
| 3   | Berg et al., 2014              | S960        | 7                | 5                | Cover plate                                 | FW                 | sl                             | HFMI              |
| 4   | Berg et al., 2014              | S960        | 7                | 7                | Butt weld                                   | BW                 | sl                             | HFMI              |
| 5   | Berg et al., 2014              | S960        | 5                | 5                | Butt weld                                   | BW                 | sl                             | HFMI              |
| 6   | Berg et al., 2014              | S1100       | 6                | 6                | Cover plate                                 | FW                 | sl                             | HFMI              |
| 7   | Berg et al., 2014              | S1100       | 6                | 6                | Longitudinal stiffener                      | FW                 | sl                             | HFMI              |
| 8   | Berg et al., 2014              | S1100       | 6                | 6                | Transverse stiffener (cruciform type)       | FW                 | sl                             | HFMI              |
| 9   | Berg et al., 2014              | S1100       | 6                | 6                | Cover plate                                 | FW                 | sl                             | HFMI              |
| 10  | Berg et al., 2014              | S1100       | 6                | 8                | Butt weld with different thickness plate    | BW                 | ml                             | HFMI              |
| 11  | Berg et al., 2014              | S1300       | 4                | 4                | Cover plate                                 | FW                 | sl                             | HFMI              |
| 12  | Berg et al., 2014              | S1300       | 4                | 4                | Transverse stiffener (cruciform type)       | FW                 | sl                             | HFMI              |
| 13  | Berg et al., 2014              | S1300       | 4                | 4                | Longitudinal stiffener                      | FW                 | sl                             | HFMI              |
| 14  | Ghahremani et al., 2015        | S355        | 9.5              | 9.5              | Transverse stiffener (cruciform type)       | FW                 | sl                             | HFMI              |
| 15  | Ghahremani et al., 2015        | S355        | 9.5              | 9.5              | Lap joint                                    | FW                 | sl                             | HFMI              |
| No. | Reference               | Steel grade | Plate thickness 1 | Plate thickness 2 | Welding specimen type                                | Welding joint type | Welding technique (cover layer) | Post-weld treatment |
|-----|-------------------------|-------------|-------------------|-------------------|-----------------------------------------------------|--------------------|---------------------------------|---------------------|
| 16  | Harati et al., 2020     | S1300       | 15                | 15                | Transverse stiffener (T joint type)                 | BW                 | sl                             | HFMI                |
| 17  | Harati et al., 2020     | S1300       | 15                | 15                | Transverse stiffener (T joint type)                 | BW                 | sl                             | Shot Peening        |
| 18  | Harati et al., 2020     | S1300       | 15                | 15                | Transverse stiffener (T joint type)                 | BW                 | sl                             | LTT Welding         |
| 19  | Lefebvre et al., 2015   | S690        | 10                | 10                | Butt weld                                           | BW                 | sl                             | HFMI                |
| 20  | Leitner et al., 2014    | S690        | 5                 | 5                 | Butt weld                                           | BW                 | sl                             | HFMI                |
| 21  | Leitner et al., 2014    | S690        | 5                 | 5                 | Transverse stiffener (T joint type)                 | BW                 | sl                             | HFMI                |
| 22  | Leitner et al., 2014    | S690        | 5                 | 5                 | Longitudinal stiffener                              | BW                 | sl                             | HFMI                |
| 23  | Leitner et al., 2014    | S960        | 5                 | 5                 | Butt weld                                           | BW                 | sl                             | HFMI                |
| 24  | Leitner et al., 2014    | S960        | 5                 | 5                 | Transverse stiffener (T joint type)                 | BW                 | sl                             | HFMI                |
| 25  | Leitner et al., 2014    | S960        | 5                 | 5                 | Longitudinal stiffener                              | BW                 | sl                             | HFMI                |
| 26  | Leitner et al., 2020    | S1100       | 6                 | 6                 | Butt weld                                           | BW                 | sl                             | HFMI                |
| 27  | Leitner et al., 2020    | S1100       | 6                 | 6                 | Lap joint                                           | FW                 | sl                             | HFMI                |
| 28  | Leitner et al., 2020    | S1100       | 6                 | 6                 | Transverse stiffener (T joint type)                 | FW                 | sl                             | HFMI                |
| 29  | Leitner et al., 2020    | S1100       | 6                 | 6                 | Longitudinal stiffener                              | FW                 | sl                             | HFMI                |
| 30  | Leitner et al., 2020    | S1300       | 4                 | 4                 | Lap joint                                           | FW                 | sl                             | HFMI                |
| 31  | Leitner et al., 2020    | S1300       | 4                 | 4                 | Transverse stiffener (T joint type)                 | FW                 | sl                             | HFMI                |
| 32  | Leitner et al., 2020    | S1300       | 4                 | 4                 | Longitudinal stiffener                              | FW                 | sl                             | HFMI                |
| No. | Reference                      | Steel grade | Plate thickness 1 | Plate thickness 2 | Welding specimen type | Welding joint type | Welding technique (cover layer) | Post-weld treatment |
|-----|--------------------------------|-------------|------------------|------------------|----------------------|--------------------|---------------------------------|---------------------|
| 33  | Ting et al., 2009             | S700        | –                | –                | Butt weld            | BW                 | sl                             | HFMI                |
| 34  | Ting et al., 2009             | S700        | –                | –                | Longitudinal stiffener | FW                 | sl                             | HFMI                |
| 35  | Yang et al., 2014             | S690        | 12               | 12               | Transverse stiffener (cruciform type) | FW     | sl                             | HFMI                |
| 36  | Yekta et al., 2013            | S355        | 9.5              | 9.5              | Transverse stiffener (cruciform type) | FW     | sl                             | HFMI                |
| 37  | Hai et al., 2015              | S690        | 15               | 15               | Butt weld            | BW                 | ml                             | HFMI                |
| 38  | Dahle, 1998                   | S700        | 12               | 12               | Longitudinal stiffener | FW     | sl                             | TIG Dressing        |
| 39  | Dahle, 1998                   | S900        | 12               | 12               | Longitudinal stiffener | FW     | sl                             | TIG Dressing        |
| 40  | Ferreira et al., 1989         | S355        | 4                | 4                | Transverse stiffener (cruciform type) | FW     | sl                             | Thermal Stress Relief |
| 41  | Ferreira et al., 1989         | S355        | 6                | 6                | Transverse stiffener (cruciform type) | FW     | sl                             | Thermal Stress Relief |
| 42  | Ferreira et al., 1989         | S355        | 12               | 12               | Transverse stiffener (cruciform type) | FW     | sl                             | Thermal Stress Relief |
| 43  | Ferreira et al., 1989         | S355        | 20               | 20               | Transverse stiffener (cruciform type) | FW     | sl                             | Thermal Stress Relief |
| 44  | Ferreira et al., 1989         | S355        | 4                | 4                | Transverse stiffener (T joint type) | FW     | sl                             | Thermal Stress Relief |
| 45  | Ferreira et al., 1989         | S355        | 6                | 6                | Transverse stiffener (T joint type) | FW     | sl                             | Thermal Stress Relief |
| 46  | Ferreira et al., 1989         | S355        | 12               | 12               | Transverse stiffener (T joint type) | FW     | sl                             | Thermal Stress Relief |
| 47  | Ferreira et al., 1989         | S355        | 20               | 20               | Transverse stiffener (T joint type) | FW     | sl                             | Thermal Stress Relief |
| 48  | Gerritsen et al., 2013        | S690        | 10               | 10               | Longitudinal stiffener | FW     | ml                             | Laser Remelting     |
| 49  | Gerritsen et al., 2013        | S960        | 10               | 10               | Longitudinal stiffener | FW     | ml                             | Laser Remelting     |
| No. | Reference                  | Steel grade | Plate thickness 1 | Plate thickness 2 | Welding specimen type | Welding joint type | Welding technique (cover layer) | Post-weld treatment |
|-----|----------------------------|-------------|-------------------|-------------------|-----------------------|--------------------|---------------------------------|---------------------|
| 50  | Mecséri et al., 2020       | S420        | 10                | 10                | Longitudinal stiffener | FW                 | sl                              | Burr Grinding       |
| 51  | Mecséri et al., 2020       | S420        | 18                | 18                | Longitudinal stiffener | FW                 | sl                              | Burr Grinding       |
| 52  | Skirko et al., 2017        | S960        | 8                 | 8                 | Transverse stiffener (cruciform type) | FW                 | sl                              | TIG Dressing        |
| 53  | Bhatti et al., 2013        | S700        | 5                 | 5                 | Longitudinal stiffener | FW                 | sl                              | LTT Welding         |
| 54  | Bhatti et al., 2013        | S700        | 10                | 10                | Longitudinal stiffener | FW                 | sl                              | LTT Welding         |
| 55  | Bhatti et al., 2013        | S960        | 5                 | 5                 | Longitudinal stiffener | FW                 | sl                              | LTT Welding         |
| 56  | Bhatti et al., 2013        | S960        | 10                | 10                | Longitudinal stiffener | FW                 | sl                              | LTT Welding         |
| 57  | Marquis, 2010              | S700        | 8                 | 8                 | Longitudinal stiffener | FW                 | sl                              | HFMI                |
| 58  | Marquis, 2010              | S700        | 8                 | 8                 | Longitudinal stiffener | FW                 | sl                              | LTT Welding         |
| 59  | Marquis, 2010              | S960        | 6                 | 6                 | Longitudinal stiffener | FW                 | sl                              | HFMI                |
| 60  | Marquis, 2010              | S960        | 6                 | 6                 | Longitudinal stiffener | FW                 | sl                              | LTT Welding         |