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Impact of thermal loading into the structural performance of ships: A review

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Abstract

The presented study reviews the recent advances done regarding the impact of thermal loading on the structural performance of ships. Firstly, the studies related to the mechanical and thermal properties of typical materials used in shipbuilding are outlined. Secondly, a brief introduction to the heat transfer analysis, Finite Element modelling and thermal stresses is provided. Finally, the review of papers dealing with the structural response of ship hull girder elements subjected to thermal loading is outlined. Two main groups of analyses are highlighted, i.e. structural performance at very low and very high temperatures. In each group, the possible future research needs are identified, and conclusions are drawn.

Keywords: ship structures, thermal loads, LNG ships

1. Introduction

The occurrence of excessive temperature within ship structural elements could be one of the reasons for structural failure, which should be considered during the design stage (Moatsos, 2005). Over 70% of offshore installation accidents are related to fires and explosions (Health and Safety Executive, 2002), and similar statistics could be found regarding ship casualties and incidents (European Maritime Safety Agency, 2019). Serious incidents were also observed due to Liquified Natural Gas (LNG) leakage

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in ships (Baalisampang et al., 2019), stored in extremely low temperatures. Therefore, there could be a variety of sources of thermal loads in ship structures, and the main sources of them could be as follows: fire loads, leakage of LNG, cargo stored in extreme temperatures (LNG, fuel, sulphur, etc.). Further, the ambient temperature of surrounding water and excessive heating of decks due to sunshine in tropical waters could also be treated as a temperature source. In such a case, the thermal stresses generated in the hull girder could contribute to the general bending of the ship. In general, with the occurrence of temperature amplitudes in ship structures, three main effects can be distinguished (Gatewood, 1957): deflection of the hull, changes in mechanical properties of the material, temperature-dependent stresses are generated.

The topic itself is in development for many years. One of the first papers published regarding the occurrence of thermal stresses could be found (Smith, 1913), where it was found that the temperature amplitude between deck and bottom, caused by the sun's rays, could lead to significant deflections in the hull. Further, this problem became of higher importance in the late 1950s due to the design and construction of ships that can carry liquefied gases at very low temperatures and liquefied sulphur at very high temperatures. Some early works related to that problem could be listed, e.g. (Corlett, 1950; Hechtman, 1956; Jasper, 1956; Meriam et al., 1958). The works were mainly oriented to investigate the influence of temperature distribution within the transverse cross-section and its impact on the generation of stresses. However, with the rapid increase of computational power and development of the Finite Element Method, more advanced analyses have become possible. This allowed not only to compute the temperature distribution within the structure, even considering unstable transient conditions, but also to identify the temperature-dependent stresses accounting for various non-linearities, such as large deflections and changes in material or thermal properties. In the last two decades, works dedicated to the impact of fires on the integrity of structures were one of the research topics previously investigated experimentally only due to limitations in the computational domain. In general, the analysis of the impact of thermal loads into the local structural response, instead of global, of various members was the main object of recent investigations.

It was identified that there is a lack of work that reviews the current advances made in the field of thermo-mechanical analysis of ship structural members, which is the objective of the presented paper. The problem is of high importance due to the possible structural failure that could be related to thermal loading. All relevant aspects of the considered problem are outlined. In the first two sections, the works regarding changes in mechanical and thermal properties of materials depending on temperature, with particular attention to steel used in shipbuilding, are provided. Further, a brief introduction to heat transfer analysis and thermal stresses, including the Finite Element method, is given. As a main outcome of the presented work, the existing knowledge regarding ship structural performance subjected to thermal loading in very high and very low temperatures is reviewed and commented on. Finally, the future research needs and perspectives are identified.

2. Mechanical properties dependent on temperature

The changes in material properties will be inherent with the temperature changes. Therefore, to model the behaviour of structures in different temperatures, information about mechanical properties constitutive laws are essential. Thus, the experimental studies can generally be divided into investigations related to mechanical properties in higher temperatures and lower temperatures regarding room temperature.

In general, with the temperature increase, the elastic modulus and yield strength will decrease. Since structural performance analysis in elevated temperatures is required in many branches, such as civil engineering (see Eurocode 3 (European Committee for Standardization, 2005)), there are many works regarding the estimation of mechanical properties in higher temperatures. A comprehensive review concerning changes in mechanical properties of steels was presented in (Seif et al., 2016), where results from around 16 sources have been combined and analyzed. The changes in both elastic modulus and yield strength are shown in Figure 1. The references for particular studies presented in Figure 1, that data were collected from, could be found in (Seif et al., 2016), e.g. data set 12 (Chijiiwa et al., 1993), data set 45 (Poh, 1998). In terms of typical structural steel used in shipbuilding, where mechanical properties at elevated temperatures were examined (Paik et al., 2021b), a similar decrease has been observed.

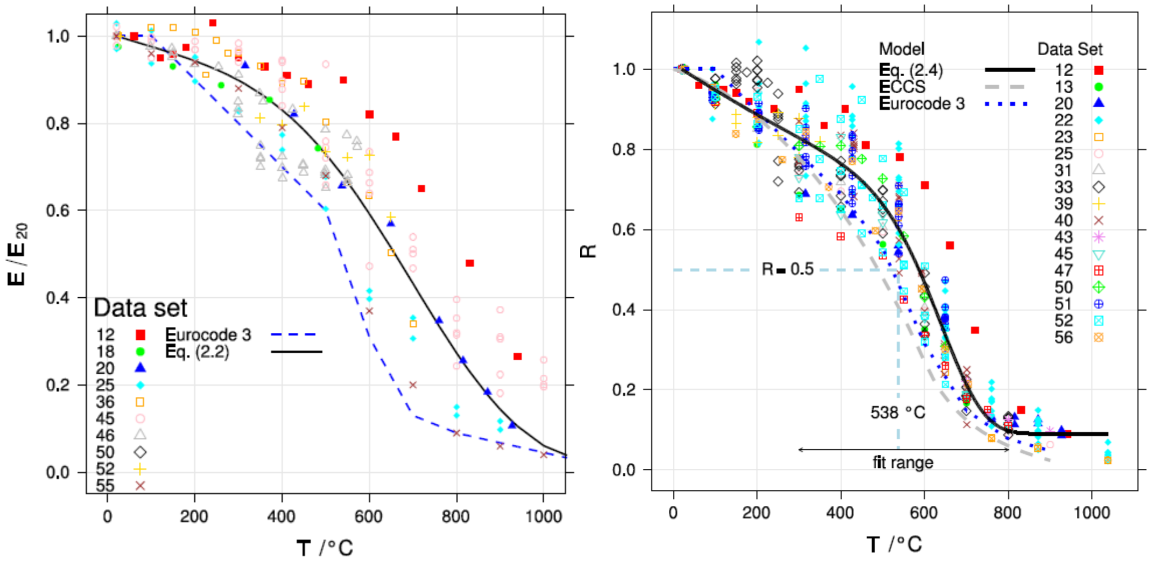

Figure 1. Changes in mechanical properties at elevated temperature: elastic modulus (left) and yield strength (right) (Seif et al., 2016).

The mechanical properties presented in Figure 1 are demonstrated as relative values concerning its values at room temperature. It is noted that the mechanical properties are reduced from the beginning. However, after reaching the value of 500 $^{\mathrm{o}}$C, the reduction is much more dramatic. The authors of the report (Seif et al., 2016) proposed empirical formulations for both elastic modulus and yield strength:

$$E(T) = E_0 \exp\left(-\frac{1}{2}\left(\frac{T-20}{639}\right)^{3.768} - \frac{1}{2}\left(\frac{T-20}{1650}\right)\right) \quad (1)$$

$$Re(T) = Re_0\left(0.09 + 0.91 \cdot \exp\left(-\frac{1}{2}\left(\frac{T-20}{588}\right)^{7.514} - \frac{1}{2}\left(\frac{T-20}{676}\right)\right)\right) \quad (2)$$

Not only elastic modulus and yield strength are reduced with the temperature elevation, but ultimate tensile strength too. Additionally, the uniform strain, where the necking phenomenon starts to occur, is also lower regarding ambient temperature. However, with the increase of temperature, the total elongation increases since the material is more plastic in general (Paik et al., 2021b).

In Figure 1, the mechanical properties obtained from experiments are compared with those used in Eurocode 3 (European Committee for Standardization, 2005). It is noted that this norm gives a conservative estimation that could be adopted in design. One needs to register that with the increase of temperature, the variations of mechanical properties increase, and the Coefficient of Variation reaches the maximum level of 25% (Seif et al., 2016). In general, Equations 1 and 2 are based on the experiments regarding the mechanical properties of carbon steel of different strengths. Thus, in principle, there can be applied in the marine field when dealing with typical structural steel of different grades. However, when dealing with stainless steel, the Eurocode 3 (European Committee for Standardization, 2005) shows slightly different constitutive laws for those materials, which are also used in the marine field for different applications.

To model the material behaviour in extremely low temperatures (e.g. storage of LNG), the mechanical properties in these conditions were investigated too. Up to now, there are various studies related to that problem, and the conclusions were rather similar between researchers. However, some differences are noted. Some first attempts to address this issue could be found in (Elices et al., 1986), where hot rolled reinforcing steels were tested at temperatures between 20 ^{o}C and -180 ^{o}C. It was found that mechanical properties increased with the decrease of temperature. Similar observations were found in (Dahmani et al., 2007); additionally, the ductility of steel decreased significantly in low temperatures. Nevertheless, by comparing with other studies (e.g. (Filiatrault and Holleran, 2001; Yan et al., 2014; Yan and Xie, 2017a, 2017b)), it was noted that the influence of temperature would be different depending on the steel type. Thus, it is hard to determine the universal model to predict changes in mechanical properties with the temperature drop.

Yan and Xie (2017b) tested the coupon specimens of three different steel grades, typically used for the construction of LNG storage tanks. The changes in elastic modulus and yield strength are presented in

Figure 2. As it can be noticed, there were observed different changes in mechanical properties dependent on the steel type.

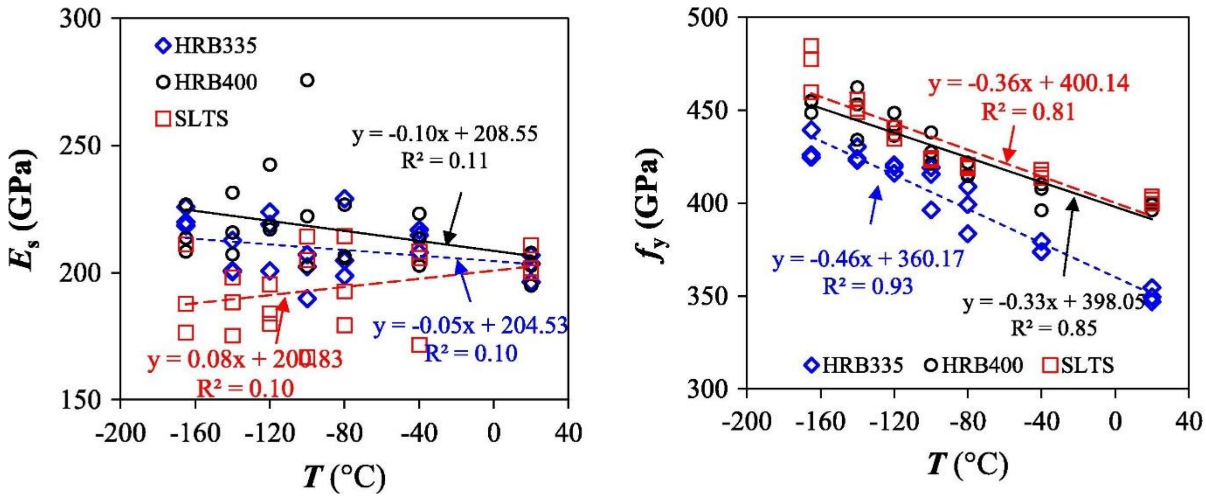

Figure 2. Elastic modulus (left) and yield strength (right) dependent on negative temperatures (Yan and Xie, 2017b).

The interesting studies related to the mechanical properties of typical shipbuilding steel in negative temperatures can be found in (Paik et al., 2020a). Authors tested steel specimens of AH32 grade within the range of temperatures from -160 ^{o}C up to 0 ^{o}C. However, in opposition to other researchers, the specimens were tested in both tension and compression. The results regarding yield strength in both tensile and compressive load are presented in Figure 3. It is noted, that below 0 ^{o}C, there is a difference between yield strength in tension and compression and increase significantly with the temperature decrease. In the case of compression stress, there is not observed a significant increase of yield strength. In terms of elastic modulus, the value was found to be constant in both tension and compression. The failure strain in tension was found to increase down to -100 ^{o}C. Below that temperature, it starts to decrease again.

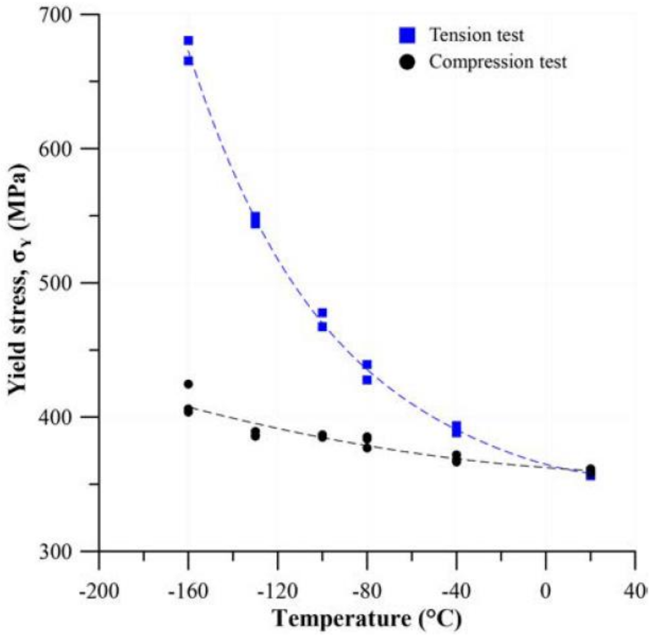

Figure 3. Yield strength for the AH32 steel in tension and compression (Paik et al., 2020a).

As can be noticed, there is hard to define strict rules that govern the changes in mechanical properties at lower temperatures, similarly as it can be done for elevated temperatures (see Figure 1). The conclusions could be different regarding material type and type of loading (tensile or compressive). Due to that, there is hard to find any normative guidelines regarding mechanical properties at lower temperatures. However, assuming the constant value of Elastic modulus, the linear analysis could be conducted.

3. Thermal properties of materials

To perform the thermal analysis in structure, one needs to determine the thermal properties of steel or other materials used. We can distinguish a couple of main properties important from the structural analysis point of view: thermal conductivity, specific heat and thermal expansion coefficient.

Thermal conductivity (k) specifies the ability of particular material to conduct the heat. The higher the conductivity of the material is, the faster heat will be transferred. Thus, the isolators are materials of very low thermal conductivity (close to 0), whereas conductors are materials with high abilities to conduct heat. The steel could be classified as a rather good conductor, with the mean thermal conductivity value at room temperature equal to approx. $58\, W/(m \cdot K)$. However, the thermal conductivity will be dependent on both steel type and temperature (Peet et al., 2011). In general, the conductivity will decrease sharply at lower temperatures (Hahn and Özişik, 2012). However, in elevated temperatures, the conductivity could increase, decrease or remain constant, depending on the chemical composition of the particular steel alloy. The thermal conductivity values of typical engineering materials in sub-zero temperatures could be found in (Marquardt et al., 2002), including standard stainless steel and Invar steel.

In the case of low-carbon steels at elevated temperatures, the Eurocode (European Committee for Standardization, 2005) gives the following expression to estimate the thermal conductivity (in $W/(m \cdot K)$):

$$\begin{cases} \lambda_a = 54 - 3.33 \cdot 10^{-2} \cdot T & for \quad 20^0C \leq T \leq 800^0C \\ \lambda_a = 27.3 & for \quad 800^0C \leq T \leq 1200^0C \end{cases} \tag{3}$$

It is noted that the conductivity of carbon steel decrease with temperature. However, in the case of stainless steel, the trend is the opposite (Franssen and Real, 2010).

The next parameter important from a thermal point of view is the specific heat capacity, which is a property informing what amount of energy must be applied to a unit of substance in order to increase its temperature by one unit. This parameter then is the ability of the material to store or release heat energy. In general, the heat capacity will tend to zero, as the temperature will tend to $0\, K$. The specific heat capacity of different materials in lower temperatures is presented in Figure 4, top (Duthil, 2015). However, in the case of temperatures above the ambient one, the specific heat capacity will increase with temperature (Kodur et al., 2010). Additionally, when reaching Curie temperature, there will be a significant drop of specific heat, which will decrease again after crossing that point. This phenomenon is reflected in both Eurocode 3 (European Committee for Standardization, 2005) and ASCE (ASCE, 1992) models (see Figure 4, bottom).

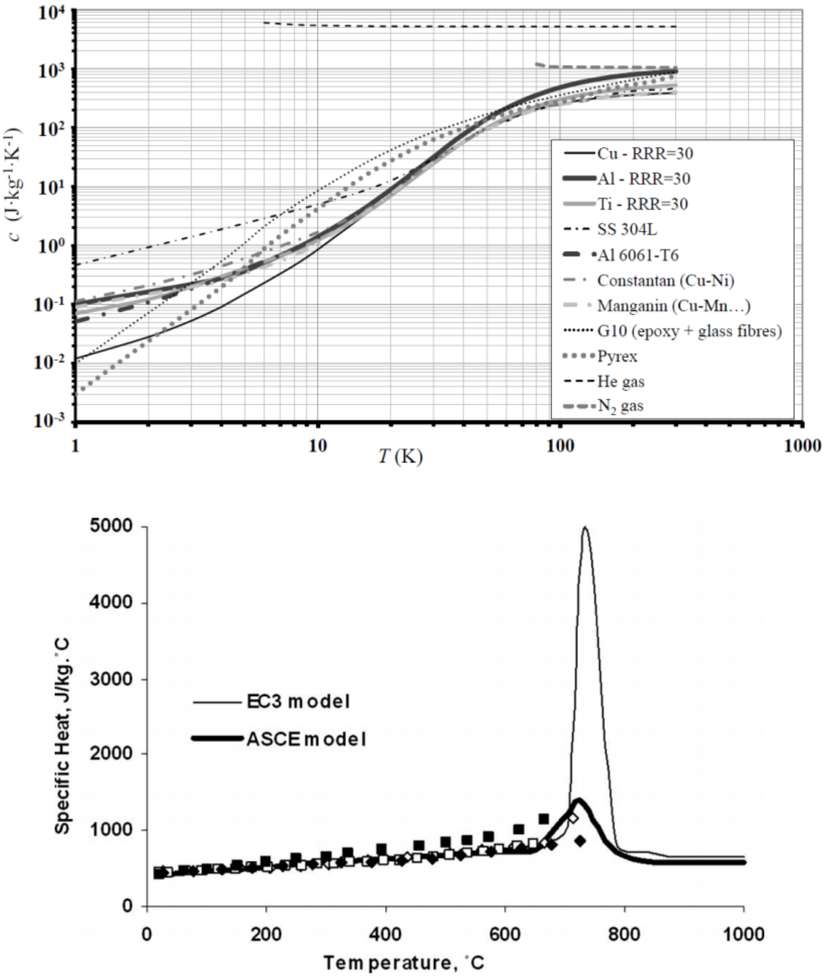

Figure 4. Specific heat of different materials at low temperatures (top) (Duthil, 2015) and specific heat of steel at elevated temperatures (bottom) (Kodur et al., 2010).

The linear expansion factor is the final thermal property that needs to be considered in the thermo-structural analysis. In general, if a structure is free of any restrains, and the temperature will increase by one unit, the linear dimensions will also increase. The parameter that determines the relation between changes in linear dimensions and temperature changes is the linear expansion coefficient. The equation will be as follows:

$$\varepsilon_T = \frac{\Delta L}{L} = -\alpha \cdot \Delta T \tag{4}$$

where ε_T is the thermal strain, $\frac{\Delta L}{L}$ is the relative change of the linear dimension of the structure, α is the thermal expansion coefficient, and ΔT is the temperature amplitude.

The thermal expansion coefficient can be determined by plotting the thermal strain in the function of temperature (see Figure 5). Considering room temperature as a reference one, the thermal strain is plotted for lower (Figure 5, left) and elevated (Figure 5, right) temperatures. The thermal expansion coefficient will be the slope of the curve at any particular temperature. In the case of steel, $\alpha = 1.2 \cdot 10^{-5}\ 1/K$, in the ambient temperature. This value is more or less valid between -120 ^{o}C up to 750 ^{o}C since the relation between thermal strain and temperature is linear. However, the coefficient decreases significantly in very low temperatures, and below -223 ^{o}C, the structure stops to compress. In case of very high temperatures, the structure stops expanding between approx. 750 ^{o}C and 860 ^{o}C, and it starts to expand again after crossing that region. It is noted, that two models are shown in the Figure 5 (right), namely EC3 and ASCE. The first one is the model suggested by Eurocode 3 (European Committee for Standardization, 2005), whereas second one is suggested by the American Society of Civil Engineers (ASCE, 1992). The ASCE model is simple linear regression, whereas EC3 model is multilinear and accounts for the constant thermal strain in the range between 750 ^{o}C and 860 ^{o}C. In this view, EC3 model is more accurate and closer to the observed phenomena.

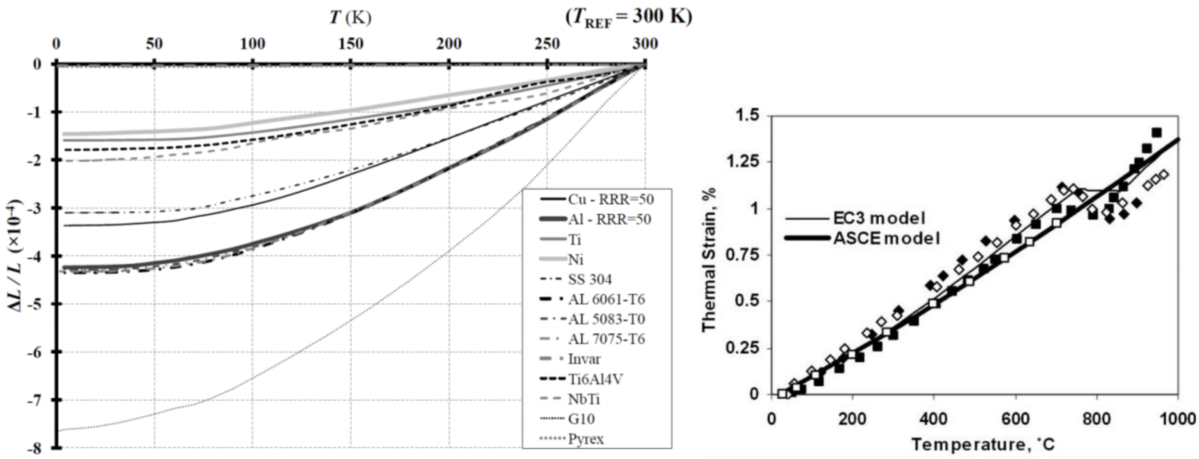

Figure 5. A thermal strain of different materials at low temperatures (temperature given in K, 0 K equals to -273 ^{o}C) (left) (Duthil, 2015) and thermal strain of steel at elevated temperatures (right) (Kodur et al., 2010).

From the literature survey, it seems that the results of the report issued by the US National Bureau of Standards (Mann, 1977) are still commonly used to predict the thermal properties of typical engineering materials in cryogenic conditions. The application of these properties could be found, e.g. in the Rules of Korean Register of Shipping, regarding the thermal analysis in LNG ships (Korean Register, 2020). In the case of elevated temperatures, the models given in Eurocode 3 (European Committee for Standardization, 2005) are usually used as a reference when dealing with steel structures. The specific heat capacity and thermal conductivity are necessary to obtain the thermal field in the structure, whereas linear expansion coefficient is crucial to determine the thermal-induced stresses.

Regarding ship structures, the thermal properties of steels of different grades will be important, since, typically there are used to build the ship hull. However, in the case of LNG ships, the properties of insulation materials will be important too. There could be given by the manufacturer, determined experimentally (Choi et al., 2012), or found in the literature.

4. Principles of heat transfer

The principles regarding heat transfer could be found in many books, e.g. (Annaratone, 2010; Linehard and Lienhard, 2019; von Böckh and Wetzel, 2012). Nevertheless, a very brief introduction is provided herein. There are existing three main heat transfer mechanisms: conduction, convection and radiation. The conduction is responsible for the heat flow inside a solid body. Convection governs the heat entering and escaping the solid body, which requires the solid body to be surrounded by a fluid (liquids and gases). Finally, radiation controls the heat escaping and entering a solid body by electromagnetic radiation; however, it is noticeable at higher temperatures. For typical engineering applications, including ship structures, heat conduction and convection is usually sufficient to model the heat transfer problems. Nevertheless, in case of fire loads, radiation cannot be neglected.

The following equation governs the heat conduction:

$$\frac{dQ}{dt} = \lambda A \frac{dT}{dx} \quad (5)$$

where dQ/dt is the rate of heat transfer, λ is the thermal conductivity (already discussed in the previous Section), A is the area of cross-section of the heat flow path, and dT/dx is the temperature gradient (given as temperature change per unit length).

Thus, if a temperature gradient occurs within the structure, heat conduction will appear too. The thermal energy will move from the region of high-temperature to the area of low-temperature.

Newton's Law of Cooling governs the heat convection:

$$\frac{dQ}{dt} = h_s A(T_s - T_m) \quad (6)$$

where h_s is surface heat-transfer coefficient, T_m is the temperature of the cooling medium (air, water, oil) and T_s is the surface temperature of the solid.

The convection coefficient will depend strongly on the medium (i.e. water, air) and the inclination of the solid surface that the heat is escaping. Additionally, we can distinguish between natural convection and forced convection. Natural convection is caused by the gravity changes between cold and hot fluids. The forced convection can be created by an external force (e.g. fan or pump). The convection coefficient h can be calculated for different heat flows and plate inclinations, e.g., external flow in vertical plate (Churchill and Chu, 1975), external flow in horizontal plate (McAdams, 1954), etc.

Finally, the radiation is the phenomenon of heat transfer, where energy is dissipated in the form of electromagnetic waves between two objects. In this case, the existence of a transferring medium is not needed. The governing equation of heat radiation is as follows:

$$\frac{dQ}{dt} = \sigma F(\varepsilon T^4 - \alpha T_a^4) \quad (7)$$

where σ is the Stefan-Boltzman constant, F is the radiation view factor, ε is the emissivity, α is the absorptivity, T is the temperature of an object and T_a is the ambient temperature.

5. FE modelling of heat transfer

The basic cases of heat transfer can be easily calculated analytically (using Equations 5 and 6). However, for more complicated cases, such as ship structure, more robust methods are needed. With the rapid growth of computational capabilities, the FE software is more commonly used for full thermal analysis (MidasNFX, 2015). Firstly, the heat transfer analysis could be conducted. In the next step, the thermally-induced stresses could be investigated too. The fundamentals regarding FE analysis of heat transfer problems could be found in books, e.g. (Huang and Usmani, 1994; Lewis et al., 2004). The more practical guides could be found too, e.g. (MidasNFX, 2015). A brief introduction regarding types of FE analysis is given herein.

We can perform linear and non-linear analyses, depending on the material properties, heat transfer mechanism, and analysis conditions. For linear analysis, the material properties (conductivity, specific heat and density) must be assumed constant, which will be invalid for most materials (see Section 2). Thus, if a significant temperature gradient is to be taken into account, the non-linearities regarding material properties need to be considered. However, to simplify the problem for many engineering applications, some mean values of material properties could be taken into account.

Further, regarding heat transfer mechanism, heat flux has a linear relationship with a temperature gradient in conduction and convection. Thus, in this two cases, the linear solver could be adopted. However, it will require constant boundary conditions (constant temperatures of heat sources). If temperature of heat sources will change with time, the non-linear solver will be essential. In the case of the radiation, there is a non-linear relationship between heat flux temperature and to account for that, only non-linear solver could be applied.

We can distinguish two main types of heat transfer, i.e. steady-state and transient. The steady-state analysis deals with the problem, where the temperature distribution within the structure will reach the constant value. Conversely, the transient heat transfer deals with the problem, where temperatures within the structure vary with time. Thus, the transient analysis could be solved only by a non-linear solver using an iterative procedure from the definition.

It needs to be highlighted that steady-state analysis could also be used in situations where temperature initially varies with time but stabilizes at a constant level. Thus, the steady-state analysis will provide information about the final state of the considered structure. The transient analysis will be used in the process of heat exchange will be of detailed interest. In most engineering applications, for design purposes, the steady-state analysis will be sufficient. If, additionally, the heat transfer via fluids will be of interest, the methods of Computational Fluid Dynamics will be needed to be employed.

6. Thermal induced stresses in structures

The mechanism that leads to the generation of stresses in structures subjected to thermal loads is presented in Figure 6. As noted, the unrestrained structural element will deform due to the thermal expansion of the structure. However, when we restrain the element from deformation, the thermal load will result in generated stresses. If the temperature gradient is positive, the stresses will be negative. As indicated before, the parameter that combines thermal strain with temperature gradient will be the thermal expansion coefficient.

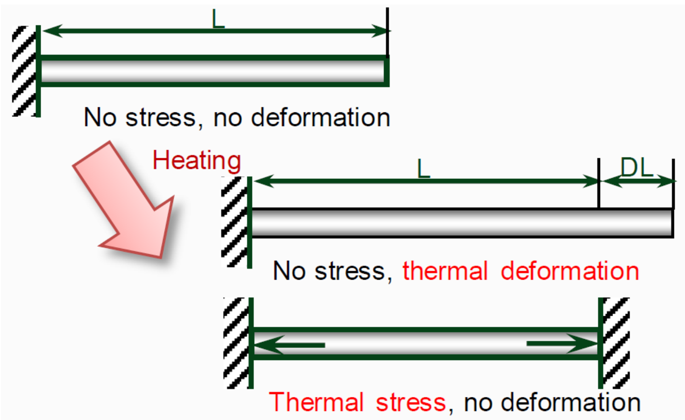

Figure 6. Mechanism of generation of thermal stresses in structures (MidasNFX, 2015).

For simple cases, the steady-state thermal stresses could be obtained analytically. Nowacki (1957) presented the solution for the steady-state thermal stresses in a thick circular plate subjected to the temperature field. In (Kulkarni and Deshmukh, 2007), the analytical solution for quasi-static thermal stresses in a thick circular plate has been proposed. The edge was restrained, and there were different temperatures in both faces of the plate. The analysis of quasi-static stresses induced by a point heat source in a thin circular plate was performed in (Deshmukh et al., 2011). As can be noticed, the analytical solutions are possible for rather simple cases; however, numerical tools need to be employed for more complex structures.

Nowadays, the Finite Element Method is typically employed to solve the problem of heat transfer as well as associated thermal stresses, especially when dealing with non-linear problems. This allows taking into account, e.g. changes of material properties with the temperature. Therefore, many examples of the application of FEM into advanced thermo-stress analysis could be found. For instance, in (Sabik and Kreja, 2015), the thermo-elastic non-linear analysis of multi-layered composite plates and shells has been presented. Other works regarding different structural elements could be found, too, e.g. beams (Hawileh and Naser, 2012; Yang et al., 2009) and plates (Alireza Babaee and Jelovica, 2021).

As given in the Introduction, the research regarding thermal stresses in ship structures was initially focused on the impact of environmental temperature on hull girder stresses. A comprehensive review regarding works related to that problem could be found, e.g. in (Moatsos, 2005). Recently, much more focus was paid to the local effects of temperature loads. In the next two chapters, the review of existing works regarding the performance of ship structures in both low and high temperatures is presented.

7. Analysis of the structural performance of ship structures at low temperatures

The majority of research related to investigating the impact of low temperatures on ship structures is devoted to the structural integrity of LNG ships. The LNG needs to be stored at an extremely low temperature of approx. -162 ^{0}C. Tanks are insulated to prevent heat penetration; however, there are no perfect resistance materials for insulation. This could lead to the significantly low temperatures existing in the hull and the generation of boil-off gas (BOG), resulting in the losses of LNG. The thermal analysis is needed for structural assessment on one hand and calculation of boil-off rate on another.

In general, we can establish two main problems that could be solved via thermo-stress analysis from the structural point of view:

- which material should be used for the hull to ensure the proper resistance from brittle fracture;
- in extreme cases of LNG leakage, will the hull structure keep its integrity.

The problem of material selection could be solved by obtaining the temperature distribution within the hull structure by steady-state heat transfer. The material for the tank containing liquid gas must remain crack resistant and ductile at extreme low temperatures. Thus, the stainless steels and 9% nickel steels could be used, since there are not showing transition from ductile to brittle behaviour. Such calculations are also required by the classification societies in the Rules dedicated for LNG ships, e.g. Lloyd's Register (Lloyd's Register of Shipping, 2016), CCS (China Classification Society, 2017), ABS (American Bureau of Shipping, 2019) and KR (Korean Register, 2020). In most cases, both analytical method and FE analysis are allowed. The LNG tanks could be divided into two groups, membrane type and independent type (International Maritime Organization, 2016). The first type is a part of the ship's hull, whereas the second is the separate structure connected with the hull by the supporting system. For membrane tanks, usually analytical computations are sufficient. However, for independent tanks, the FE analysis needs to be employed.

An example of such calculation for membrane type tank could be found in (Wang et al., 2015). The temperature field within the hull structure of the LNG-FSRU (Liquefied Natural Gas – Floating Storage Regasification Unit) ship has been established using both analytical method (which utilizes common equations regarding heat transfer, e.g. Eq. 5 and 6) and FEM, and the temperature distribution for typical transverse bulkhead is presented in Figure 7. As can be noticed, for steady-state transfer, the analytical approach is consistent with the FE calculations; however, it requires higher computational effort.

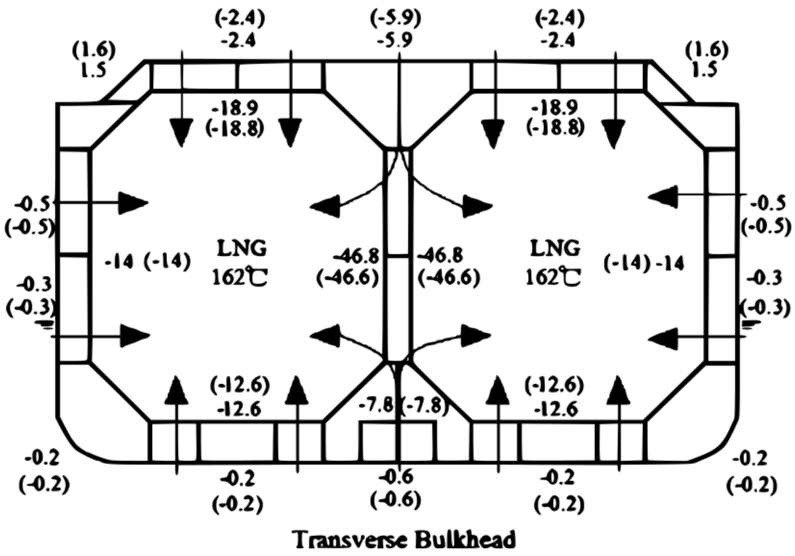

Figure 7. The temperature distribution of typical transverse bulkhead (Wang et al., 2015), values in bracket are the results of the simplified analytical method.

The Mark III membrane type tank was evaluated in (Miana et al., 2016) using four different numerical approaches. The main outcome was that the reduced models, where multi-layer insulation was changed by single-layer insulation with equivalent thermal properties, were found to be effective in reducing modelling effort. The thermal insulation characteristics of type-B LNG carriers were studied in (Niu et al., 2017), and the numerical thermal analysis of new type KC-1 LNG membrane tanks has been performed in (Jeong et al., 2017; Jeong and Shim, 2017). Other similar studies could be found in (Kim et al., 2018; Lu et al., 2016; Song et al., 1999; Wang et al., 2013; Wu et al., 2020). Interesting research has been done in (Hoang and Choung, 2021), showing that the accuracy of the calculated temperature distribution will be strongly dependent on assumed heat transfer coefficients. The application of coefficients recommended by KR (Korean Register, 2020) and calculated via in-house software resulted in differences in temperature distributions, possibly impacting the material selection during the design stage. In almost all referred studies, the steady-state FE thermal analysis was sufficient to find the temperature distribution within the hull structure.

Another type of analysis is the assessment of the ship structural response due to the accidental leakage of LNG. This could result from harsh environmental conditions, e.g. thermal stresses caused by the temperature difference between LNG and ambient temperature, LNG sloshing in heavy weather conditions (Kontovas and Psaraftis, 2009). Such leakage can have serious effects on the carrier's structure, including damage of the hull.

The method, allowing for the investigation of the temperature distribution throughout the insulation wall of the cargo containment system in LNG ships, was proposed in (Lee et al., 2011). The results of computations showed good agreement with the experimental data. The analysis of leaked LNG flow in cargo containment system (Mark III membrane-type system) and its thermal effect was presented in (Choi et al., 2016), where numerical calculations and experiments showing the behaviour of the hull's plate under thermal load were carried out. The maximum diameter of the leakage's hole was found not to exceed 2 mm. In such conditions, the temperature of the hull's plate will not be lower than the temperature of the transition from ductile to brittle behaviour of steel. The impact of LNG spill on the typical marine structure was investigated in (Baalisampang et al., 2019), where the transient thermal analysis was conducted. The thermal stress was used to evaluate the possible crack propagation in a plate. It was found that after LNG release, the immediate crack propagation will not be observed. Nevertheless, it will have a significant impact on the overall operational life of the structure. Some other works related to that problem could be found in (Kumazawa and Whitcomb, 2008; Nam et al., 2021).

The lower temperature of the structure could impact not only the local strength of the ship structural elements but also the structural response due to the acting of global hull girder loads. Therefore, the series of experiments on the ultimate strength of the typical stiffened panel composing ship hull was also done in (Paik et al., 2021a, 2020a). The stiffened plate structure has been tested at a temperature of -80^{o}C (Paik et al., 2021a) and cryogenic conditions (Paik et al., 2020a). Both studies were the continuation of the experiments performed at room temperature (Paik et al., 2020b). The considered material was the AH32 shipbuilding steel. It has been observed that the ductile failure was the primary reason for the panel collapse (buckling and plastic deformation) at room temperature. A similar observation has been achieved for the panel tested at the temperature of -80°C. However, the ultimate strength value was higher concerning the room temperature, mainly due to the higher yield strength value.

In contrast, the collapse at the cryogenic conditions was caused by a brittle fracture, and part of the structure was sharply torn outed. This could lead to a catastrophic event in a real LNG ship. The comparison between failure modes at different temperatures is presented in Figure 8. The numerical models were also developed employing the non-linear FE method. The material properties were temperature-dependent and determined based on experimental testing. Additionally, the transition from ductile to brittle behaviour of steel has been taken into account. As a result, the ultimate strength results were in a quite good match with the numerical model.

Figure 8. The stiffened panel collapsed at -80°C (Paik et al., 2021a) (left) and at cryogenic conditions (Paik et al., 2020a) (right).

There is no research on the impact of very low water temperatures on ships operating in arctic regions on the structural response, that will employ heat-transfer analysis similarly to low-temperature cargo loads or fire loads. Probably this is caused by the relatively lower temperature gradient and subsequent stress levels that are generated due to that phenomenon. However, in the case of arctic water regions, much more research is related to the ice loads, which are the type of impact loads that could cause serious structural failure, especially regarding the bow region (Li et al., 2021). The review of works related to that problem could be found in (Kendrick and Daley, 2011).

Based on the presented studies, it could be concluded that the calculation of temperature distribution within hull structure due to the existence of low-temperature cargo is rather well developed. For such cases, the steady-state heat transfer analysis employing the FE method is efficient. However, attention should be drawn to the determination of heat transfer coefficients. For more advanced problems, such as leakage of LNG, the much more advanced simulations via either CFD or transient FE method are needed.

8. Analysis of the structural performance of ship structures in high temperatures

The research related to high temperatures' influence on ship structural response could be classified into two main groups, i.e. impact of high-temperature cargo (e.g. sulphur) and accidental fire loads. Additionally, thermal analysis is commonly used in the problem of welding simulation.

The thermal stress caused by the high cargo temperature could be dangerous. In (Sole, 1983), it was found that such thermal loading could even result in a partial yield of the ship structural elements. The temperature distribution within integrated type liquid heated cargo carrier was evaluated in (Nobukawa et al., 1993) via FE analysis, and results were compared with experimental measurements. In (Teng and Gu, 2003), the thermal-stress analysis using the FE method was carried out for single-side and double bottom vessel loaded with high-temperature cargo. In addition, the simplified analytical method was proposed, too, showing good agreement with FE computations. The study revealed that the thermal stresses have a significant magnitude in longitudinal and transverse directions, which cannot be neglected during the design stage. Similar conclusions were drawn in (Li et al., 2017), where the temperature distribution in the chemical tanker was analyzed and its impact on the structural response. Similarly to the calculation of temperature distribution in LNG ships, the steady-state heat transfer analysis with the adoption of FE analysis was sufficient to solve such problems.

One of the most dangerous occurrences during the exploitation of ships are fire spreads. Since at higher temperatures, in general, material properties deteriorate, the possibility of serious structural failure is very high. To avoid that, the analysis regarding possible fire impact into structural response could be performed. Recently, some research related to that problem has been observed.

The numerical simulation using transient thermal FE solver of fire resistance of steel ship bulkheads has been performed in (Gravit and Dmitriev, 2021), and the results were compared with the available experimental data. The two steel deck bulkheads with mineral wool fire protection were investigated with different fire resistance limits. The insulation has been made from mineral wool with the thickness of 90 mm in plate and 140 mm in stiffener. The furnace temperature has considered raising from room temperature up to 1080 ℃ after 120 minutes. The example of temperature distribution within the bulkhead is presented in Figure 9. The experimental study regarding robustness in the fire of lightweight ship bulkheads was performed in (Hulin et al., 2019), where steel, aluminium and composite structures were tested. It was found that the metallic structures did not fail after a particular time of fire exposure, whereas composite bulkheads failed, mainly due to their decreased mechanical properties. Thus, more effort is needed to define the fire-resistance criteria in the case of composite structures. The new generation of fire protective coatings for composites was investigated in (Asaro et al., 2009), showing its potential.

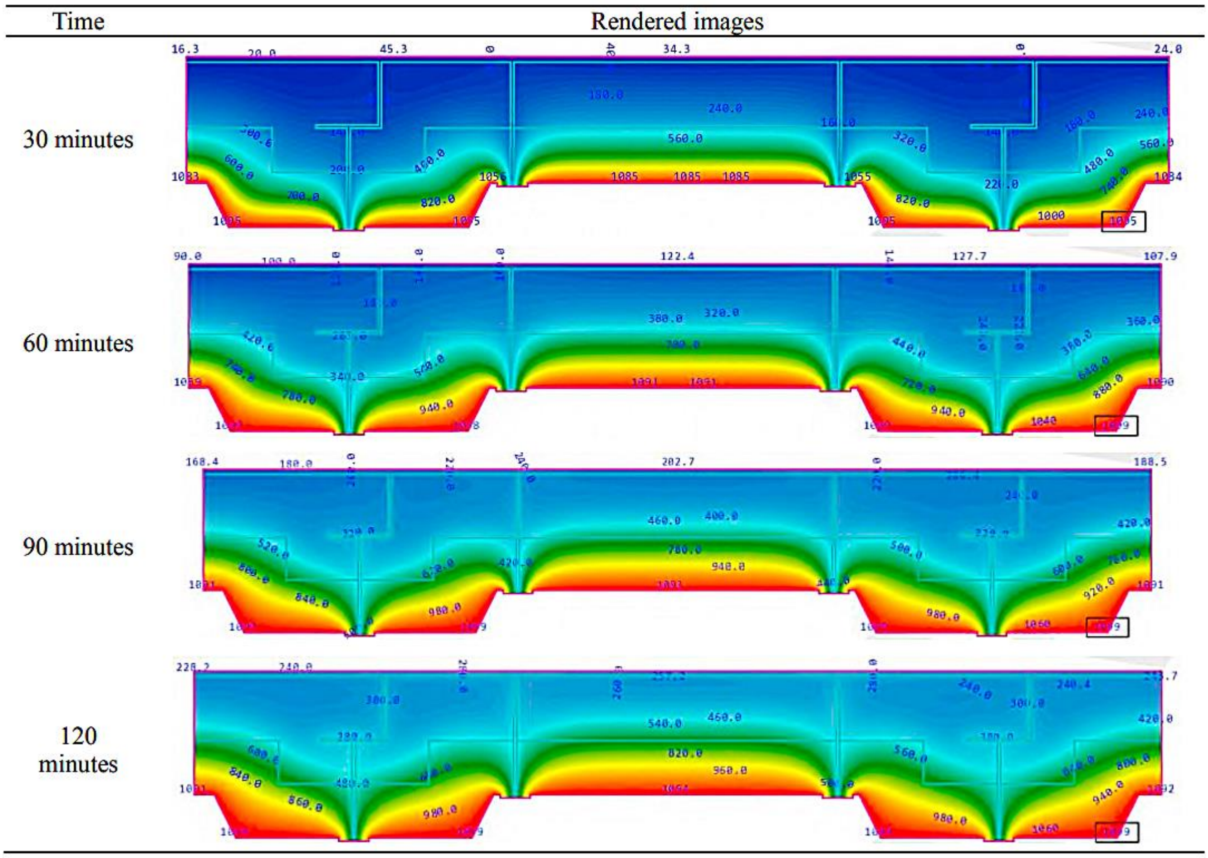

Figure 9. Temperature distribution within bulkhead (Gravit and Dmitriev, 2021).

Very recently, there were observed works related to the ultimate strength of stiffened panels in fire conditions. The full-scale fire testing of steel stiffened plate structure under lateral patch loading with (Paik et al., 2021c) and without (Paik et al., 2021b) passive fire protection was performed. In the first case, the transverse frames were insulated using cerawool, whereas plating and stiffeners remained unprotected. The results clearly demonstrated the efficiency of passive fire protection. In the unprotected panel, the deformations increased dramatically, which led to the pre-mature collapse of the entire structure. On the other hand, the temperature of protected transverse frames remained low and structural collapse was similar to that observed in normal conditions. The continuation of these studies was performed in (Ryu et al., 2021), where FE transient thermal elastic-plastic large-deformation analysis was performed, and results were compared with experiments. The numerical modelling was found to be efficient in this case; however, the heat transfer coefficients and material properties as a function of temperature need to be defined properly, as there are very influential to the results. Further, the radiation cannot be neglected in the case of fire loads, and a major part of the total heat is transferred via this mechanism. The comparison in failure modes of panels with protected and unprotected transverse frames is presented in Figure 10. Another numerical study related to that problem was performed in (Cai Xu et al., 2021), where collapse strength of stiffened panels subjected to localized thermal load with different areas (simulating fire load) was analyzed. It was found, that thermal loads will cause biaxial stress-state and the panel capacity could be significantly lower compared to the room temperature conditions. Analysis of fire impact into another types of ship and offshore structures could also be found, e.g., helidecks (Kim et al., 2016), container structures (Zha and Zuo, 2016), offshore platforms (Manco et al., 2021, 2016).

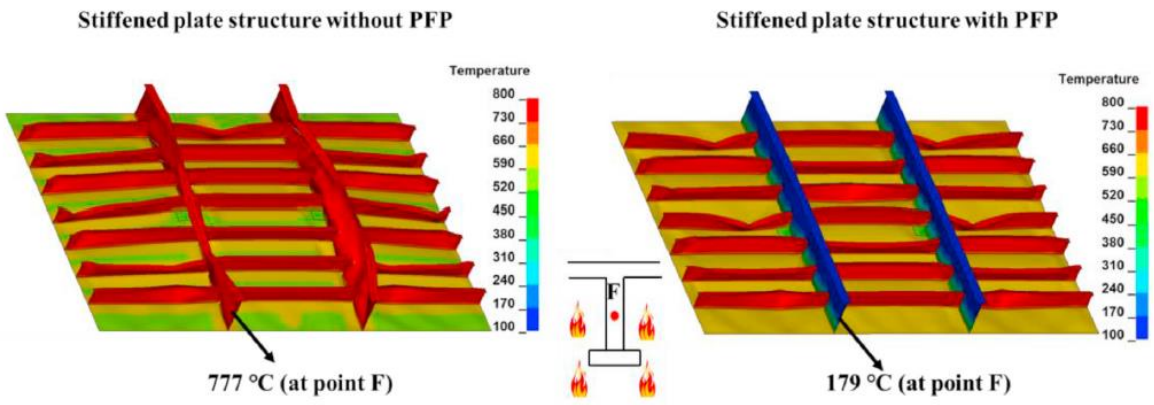

Figure 10. Comparison between failure modes of a stiffened panel with protected and unprotected transverse frames (Ryu et al., 2021).

Another issue related to the thermal analysis of ship structural elements is the simulation of welding, where recently significant research effort has been observed. Due to the existence of very high temperatures, after welding, residual stresses and deformations occur. Initially, sample cases of thermomechanical analysis of the welding process were conducted, such as (Friedman, 1975) or (Hibbitt and Marcal, 1973). With the development of computational power, advanced thermo-mechanical simulations of more advanced welded structures became possible. In fact, there was observed extensive research interest in that topic, especially regarding typical ship structural elements. Examples of such analysis could be found in (Gannon et al., 2010), where Gaussian heat source models were adopted to analyse welding sequence's effect into residual stresses and distortions in flat-bar stiffened panels. The deformations in fillet-welded joints were investigated in (Deng et al., 2007) utilizing both experiments and 3D thermal elasto-plastic FE modelling, and good agreement has been achieved. The numerical analysis of residual stresses in both butt-welded and fillet-welded plates has been performed in (Tekgoz et al., 2015). Many other works related to that problem could be found, e.g. in (Gery et al., 2005; Hashemzadeh et al., 2021; Ma et al., 2015; J. Wang et al., 2015; Wang et al., 2012; Zhang et al., 2021).

9. Conclusions

The presented paper provided a review of works done so far regarding thermo-mechanical analysis of ship structures. Based on that, several important conclusions and possible future research directions could be identified.

Although there are existing studies related to the mechanical properties of steels in different temperatures, still there are some gaps. There are much more studies dealing with high temperatures in comparison to extremely low temperatures. In the first case, there are established standards that could be easily applied in the design. In the latter case, the existing research is rather limited, especially regarding typical materials used in shipbuilding. Further, by comparing different studies, there cannot be established one trend. Thus, more research is needed to form standards that could be easily applicable in practical engineering. Similarly, more studies related to the thermal properties of materials could be conducted.

The impact of extreme temperatures on structural performance is evident. In lower temperatures, there is a risk of brittle fracture of the material. In significantly high temperatures, the material properties deteriorate, and extensive plastic deformations will be observed. The FE method is a very efficient tool to predict structural behaviour in such an environment, subjected to the condition that material and thermal properties and heat transfer coefficients are properly defined.

For LNG ships, the methods to determine the temperature distribution within hull girder due to the existence of low-temperature cargo are rather well established. Both numerical and analytical methods were found to be good tools for such an analysis. There are also existing guidelines of Classification Societies concerning that topic. However, in the case of determination of stresses generated due to thermal loading, including an accidental spill of LNG, there is a rather limited number of works. Partially this could be related to more advanced modelling that should be employed in such cases, including transient thermal FE solver and eventually CFD techniques. Furthermore, there is only a little research on the impact of cryogenic conditions on the structural response of stiffened panels, which is a typical element composing hull girder. In that matter, more research is still needed to properly understand the behaviour of larger structural components in such conditions. In future, the behaviour of the entire hull girder structure impacted due to thermal loads should be investigated, too, and some practical design formulations should be developed.

The impact of high-temperature cargo into structural response could be efficiently solved with the use of staeady-state heat transfer. Concerning accidents related to fire spread, current computational power enables to perform such analyses and very recently, more activity in that field was observed. However, most of the research focused on the impact of fires on the local strength of members, such as bulkheads or stiffened panels. There are no studies related to the global response of ship hull girder subjected to such accidental loading conditions. Finally, significant work has been done with relation to welding simulation and its impact into stresses and distortions of ship structural elements. In most problems, Gaussian heat source was applied to simulate temperature input and FE results were very close to those obtained experimentally.

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