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Introduction

I.1 History of Fatigue

The history of fatigue of metals, components, and structures goes back to the 1830s when failures of chains in mines were reported due to dynamic loading, and fatigue testing of these chains was performed for mitigation (Schütz 1996). In association with this, the first wires were invented to avoid the problems with fatigue of the chains. Since then, up until year 2000, around 100,000 papers related to fatigue were published (Schijve 2003, 2009). With so much published literature available, providing a broad and objective historical overview would be highly challenging. Thus, the historical presentation provided here is limited to those aspects that are of most relevance as background for this book. Reference is made to Schütz (1996), Stephens et al. (2001), and Anderson (2005) for a more detailed historical presentation related to fatigue.

The term "fatigue" is apparently first mentioned in the literature in 1854, by an Englishman called Braithwaite. In his paper, Braithwaite describes many service fatigue failures of brewery equipment, water pumps, propeller shafts, crankshafts, railway axles, levers, cranes, and so on. At about the same time many disastrous railroad accidents occurred, such as one on 5 October 1842 when an axle broke at Versailles due to fatigue and the lives of 60 people were lost. Failures of railway axles became a serious problem and as late as in 1887, an English newspaper reported "the most serious railway accident of the week." In many cases these accidents were due to fatigue failures of axles, couplings, and rails.

In some publications, the fatigue strength in terms of S-N curves is presented as "Wöhler curves" that are named after the work that Wöhler performed in Germany to determine the fatigue strength of railway axles based on fatigue testing in the period from 1860 to 1870. Already in 1858, Wöhler was measuring the service loads on railway axles using self-developed deflection gauges. He also introduced the concept of safety factors, where two sets were needed: one for maximum stress in service in relation to static strength, and the other for allowable stress amplitude under dynamic loading. The safety factors were provided for ensuring design for infinite life. The factors were valid only for un-notched specimens, and fatigue testing was recommended for other geometries. Wöhler presented his test data in tables. His successor, Spangenberg, started plotting these data into curves, using the form of a

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linear abscissa and ordinate. In 1910, an American named Basquin plotted the same data into a log-log format, in the same way as S-N curves are presented in fatigue design standards today.

At this time constant fatigue life diagrams were also developed in which the effect of static loading (maximum stress or stress ratio) was included in addition to the stress range, as this parameter was necessary for inclusion in bridge design. The first constant fatigue life diagram was published by Gerber in 1874, based on an assessment of Wöhler's test data. Other diagrams provided in the literature are derived from, for example, Smith in 1880, Goodman in 1899, and Haigh in 1917, in which relationships between stress amplitude and mean stress were presented. A more conservative diagram referred to in the literature for this is from Soderberg in 1930 (Sendeckyj 2001).

Fatigue failures in aircrafts from the late 1920s resulted in research to investigate representative long-term loading and fatigue capacity of aircraft structural components. Component testing became part of the qualification procedure for new elements. After World War II, it had become common practice to perform testing of large components of aircrafts in fatigue as opposed to small-scale test data. However, failures continued to occur, resulting, for example, in the Comet crashes in 1954. These accidents were later found to be due to unsatisfactory detailing of the corners of the windows in combination with an erroneous test procedure that had provided compressive residual stresses at the hot spot areas, such that the actual capacity differed from that of the laboratory test component. This fact does not only demonstrate the importance of a good detailed design in order to achieve sufficient fatigue capacity but also shows the need for performing realistic component testing in the laboratory. It is important that the structural geometry of the component and the fabrication are representative for the actual structure in terms of boundary conditions and loading. It was also realized after the failures of the Comet airplanes that these structures were not fail-safe (Edwards 1988). After these accidents, the requirements for component testing in the aircraft industry were improved. It should also be mentioned that a high-strength aluminum alloy had been used in the Comet airplanes, and it is known that the fatigue strength of a material does not necessarily correspond with the material strength. Fatigue crack initiation in the base material is considered to be improved, see Section 4.1.5, while crack growth parameters are considered to be rather constant with increasing material tensile strength, see also Section 16.11. The crack growth parameter is considered to be more a function of the Young' s modulus of the material used than of the material strength. Furthermore aircraft accidents from the late 1960s led to the development of enhanced research programs on fatigue strength based on fracture mechanics. A near-fatal accident with a Boeing 737 in 1988 resulted in the initiation of investigative activities regarding the structural integrity of old and poorly maintained aircrafts.

Professor Bauschinger of the Technical University of Munich had already in 1881 observed that the elastic limit of materials changes under repeated stress cycles. This was also the basis for the hypothesis by Manson and Coffin in the 1950s, which is still used for assessment of low cycle fatigue (Manson 1954; Coffin 1954, 1984). Low cycle fatigue is defined as stress ranges leading to repeated plastic strain during loading and unloading, such that elastic shakedown does not occur during a load cycle. Shakedown is understood to mean that the material has elastic behavior after it has yielded during large load amplitude; see also Section 3.3.2.

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Manson and Coffin described the behavior of materials under cyclic inelastic strain amplitudes by a four-parameter formula, creating a new field of activity called “low-cycle-fatigue” (LCF) that is further described in Section 3.1. In 1903, two Englishmen, Ewing and Humfrey, described the so-called slip band on the surface of rotating bending specimens. Later, in the 1930s, Polany and Orowan presented the dislocation theory, and this became the basis for many metallurgical papers on fatigue of metals. Orowan suggested that fatigue initiation is a process of cyclic shear hardening that, after depletion of the local ductility, leads to fatigue cracking. The effect of notches on the fatigue capacity of structural components was known before Wöhler performed his work. He thus recommended special fatigue tests for sharply notched specimens. In 1898, Kirch calculated that the elastic stress concentration factor for a hole in an infinite body was equal to 3.0. Analytical derivation of stress concentration factors at notches in machine components were derived by advanced mathematics combined with linear elastic theory of solids; an overview of stress concentrations around holes was presented by Johnson (1961). Measurements of stress concentrations were achieved by photo-elasticity from around 1930, and around 1970 it became normal practice to analyze stress concentrations in detail by the finite element method that had been developed during the 1960s.

In 1937, Neuber published the first comprehensive book on the theoretical calculation of the stress concentration factor K_t and also the fatigue notch concentration factor K_f. The German Thurm had previously observed in experiments that notched specimens showed a longer fatigue life than was predicted by the theoretical elastic stress concentration factor; the difference between these factors increases with increased notch effect, or with a reduced radius at the region showing the largest stress. This difference was also found to be material-dependent and the effect was described by a notch sensitivity factor that is dependent on both material and notch radius. Neuber’s book was written in German but was translated into English in 1946, and some of Neuber’s work is included in Peterson’s Stress Concentration Factors from 1953, which is a renowned book for everyone who works with fatigue of machine components. This book is still recommended for background on the notch effect and notch sensitivity, and for an explanation of elastic stress concentration factors as compared with fatigue notch concentration factors. In the early 1950s, the National Advisory Committee for Aeronautics (NACA) made an attempt to transform the calculation of the fatigue stress concentration factor, K_t, into engineering practice, based on Neuber’s material constant. However, the results were found to be of insufficient accuracy and the experimental effort required was too great. Thus, the concept of notch sensitivity is considered to be of limited use for detailed calculations today. Nevertheless, it is useful for a more qualitative understanding of the physical fatigue behavior of notched specimens.

After the 1980s a notch stress method based on a linear elastic finite element analysis has been developed, Radaj (1996) and Radaj et al. (2006). This approach has been linked to a notch stress S-N curve and is frequently being used by researchers and also by the industry in more special cases. A more detailed background for this methodology is presented in Section 9.6.

Fatigue tests are normally performed under a constant amplitude loading. However, many dynamically loaded structures are subject to variable amplitude loading. Therefore, different test spectra representing long-term dynamic loading were developed for fatigue assessment in the automobile industry, the aircraft industry, and, later, in the offshore industry. Reference is made to Section 10.2 for an example of transformation of a long-term stress range distribution into a constant amplitude loading.

Most marine structures are subject to variable amplitude loading, and this is also the load condition for many other structures, such as components in aircrafts, automobiles, and cranes, among others. In addition to requiring load spectra that are representative for long-term cyclic loading, criteria must be defined regarding how to compute fatigue damage under variable amplitude loading. In 1924, Palmgren, a Swede, published a paper (in German) on the lifetime of ball supports. This paper included not only a fatigue damage hypothesis for variable amplitude loading but also a numerical description of a probability of survival for fatigue-loaded ball bearings. An identical damage-accumulation hypothesis was presented in 1937 by Langer, an American who was probably not aware of Palmgren's work. He separated fatigue into fatigue crack initiation and fatigue crack growth, and suggested a damage sum equaling 1.0 for each of these phases. The linear fatigue damage accumulation hypothesis was presented again in 1945 by Miner, and he also performed some testing to check out his hypothesis. This linear damage accumulation has since been named the Palmgren-Miner rule. This is further assessed in Section 3.2.3.

The accuracy of the fatigue damage hypothesis is also linked to how the design S-N curve is established. Fatigue testing under spectrum loading is needed in order to determine the shape of the S-N curve in the high cycle region at the fatigue limit as the number of cycles beyond the fatigue limit becomes "infinite" or very long if the stress range in constant amplitude tests is less than the stress range that corresponds to the fatigue limit. Such test results are also denoted as "run-outs"; see also Section 3.2.2. Fatigue testing relevant for design of steel structures under spectrum loading has been performed since the 1980s as described in Section 3.2.3. The uncertainty related to variable amplitude loading is also assessed in Chapter 12. This issue is still being debated, and different recommendations on the position of the fatigue limit and change in slope in the S-N curves are found in different design standards (e.g., EN 1993–1–9:2009, ISO 19902 (2007), and BS 7608 (2014)).

It has been a challenge to develop a counting method for cycles and stress ranges that represents the physical behavior of a fatigue damaging process in a reliable manner. Several proposals for counting methods have been presented in the literature; seven different methods for cycle counting were described in a paper by Schijve in 1961 (Schijve 2009). He was closely involved in assessment and testing of components under variable amplitude loading, and considered that the rainflow counting method, published by the Japanese Matsuishi and Endo in 1968, fulfills the requirements of an acceptable counting method. At the same time, a Dutchman, DeJonge, also published the "range-pair-range," which is the same as the rainflow procedure. Statistics were needed for assessment of test data due to scatter. Weibull in Sweden carried out thousands of fatigue tests on bolts and aluminum specimens to prove his distribution and to obtain numerical data on the standard deviation of the number of cycles to failure. His work was published between 1947 and 1955. His two-parameter statistical distribution, with a shape parameter and a scale parameter, has also become important for description of long-term stress range distribution for fatigue analysis of marine structures. Reference is also made to Chapter 10 of this book.

Wöhler had already been introducing the concept of safety factors in fatigue design in around 1860. During the 1930s it became more obvious that fatigue test

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data were associated with uncertainties, while the safety philosophy also became an issue for discussion in the industry. The concepts of "fail-safe" and "safe life" had been introduced in the 1930s, with "safe life" meaning that an aircraft component had to be scrapped after a specified service life. A better alternative to this is to have a "fail-safe" aircraft, which means that failure of a primary member does not endanger flight safety. After the Comet accidents it was found that it was possible for the aircraft industry to achieve design solutions that could be considered "fail-safe." Using this approach, aircraft can be regularly inspected for fatigue cracks and reliability is significantly improved today as compared with the 1950s.

In 1920, Griffith, of the Royal Aircraft Establishment in the United Kingdom, developed the basis for use of fracture mechanics for assessment of overload rupture with cracks present in the material; at that time it was only applicable to brittle material, such as glass. Irwin developed the energy release concept, including the effect of plasticity, in around 1956. Westergaard (1939), Irwin (1957), and Williams (1957) extended the information about stresses and displacements around crack tips and the concept of stress intensity factors was developed. Reference is also made to Sih and Liebowitz (1968) for their overview chapter on mathematical theories of brittle fracture (Liebowitz 1968). In 1961, Paris developed a fatigue crack growth equation demonstrating that an increment in crack growth during a stress cycle can be related to the range in the stress intensity factor during that cycle. This equation soon became popular and was later extended in a number of ways to account better for mean stress effect and material fracture toughness; see also Section 16.2. In the United Kingdom the crack tip opening displacement (CTOD) parameter developed by Wells became extensively used in fracture mechanics during the 1960s. The CTOD design curve was developed and used in design assessment of the first oil platforms built for the North Sea in the 1970s; for further information, reference is made to Wells (1969), Burdekin and Daves (1971), the first draft proposal for CTOD testing by BSI (1972), and Burdekin (1981). In Norway fracture mechanics was used already in the beginning of the 1970s as a tool to establish rational acceptance criteria in relation to non-destructive testing techniques and for documentation of leak-before-failure in welded connections in spherical tanks in ships for transport of liquefied natural gas (LNG) made of nine percent nickel steel and of aluminum alloy 5083-0; ref. Kvamsdal and Howard (1972), Tenge and Solli (1973), Aamodt et al. (1973), and Tenge et al. (1974). More information on the historic development of fracture mechanics can be found in Hellan (1984), Anderson (2005), and Macdonald (2011). Reference is also made to Section 16.6.

After World War II, welding became the normal method for making connections between plates. S-N data were derived from fatigue testing of different types of welded connections, and nominal stress S-N curves were established for design purposes; see, for example, Gurney (1976). These S-N curves were included in the British Standard (BS 5400) for bridge structures (1980) and in the Department of Energy Guidance Notes for offshore structures (1984). Later these S-N curves were used in the Health and Safety Executive (HSE) Standards and were also copied into the ISO Standard for Design of Offshore Structures, ISO 19902 (2007). These curves are still referred to in the latest revision of BS 7608 (2014) issued as a guide for design and fatigue assessment of steel products. Similar S-N curves for different structural details have also been included in fatigue design standards in other countries.

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Most design S-N curves in standards are made for air environment assuming that the structures are sufficiently corroded protected. For fatigue assessment of offshore structures also S-N curves for seawater with cathodic protection were developed in the 1980s; see Sections 4.1.6, 4.1.7 and 4.7.

Many of the railway and highway bridges built in the first half of the 19th century are still in use, despite the fact that their planned technical life span is already completed. A large percentage of these bridges are more than 50 years old, and about 30% of them are more than 100 years old (Haghani et al. 2012). These bridges are currently being subjected to increased traffic intensity and higher traffic loads in order to meet the requirements for more efficient transportation systems. This results in fatigue problems in a number of different details. This information is considered useful as feedback for bridge designers such that details can be improved for new constructions. Many of the reported fatigue cracks are caused by secondary effects, so-called deformation-induced cracking. This type of fatigue damage is often the result of secondary restraining forces generated by some kind of unintentional or overlooked interaction between different members in the bridge. Poor detailing, along with unstiffened gaps and abrupt changes in stiffness at the connections between different members, also contributes to fatigue cracking in many details. More details and learning from this can be found in Dexter and Ocal (2013). Reference is also made to the state-of-the-art review on fatigue life assessment of steel bridges by Ye et al. (2014).

During the 1980s it became more common to analyze structural details by the finite element method. In many cases it was difficult to use the calculated stresses from finite element analysis together with nominal stress S-N curves for calculation of fatigue damage, as the calculated stresses also partly included effects from the structural geometries that were included in the analysis models, which also were accounted for in the nominal stress S-N curves. Thus, part of the stress due to the detail became included twice, leading to a conservative fatigue assessment. This resulted in the development of structural stress methods and corresponding hot spot stress methods that can be used when finite element analyses of structural components are performed; see, for example, Fricke and Petershagen (1992) and Fricke (2003). This has also resulted in the development of alternative analysis methods based on local approaches since the beginning of the 1990s, as explained more in detail in Chapter 9.

Installation of fixed offshore structures (jackets) in more harsh environments such as in the North Sea resulted in a need for improved fatigue analysis procedures, and significant developments were made on fatigue assessment of tubular joints from the end of the 1970s through 1980s; Chapter 8 describes this in more detail. The first jacket structures installed in the North Sea were mainly designed with respect to the Ultimate Limit State. However, in the late 1970s it had become practice to analyze jacket structures with respect to the Fatigue Limit State. The same practice was not introduced for floating platforms until after the *Alexander L. Kielland accident*.

In March 1980, the accommodation platform *Alexander L. Kielland* capsized in the North Sea with 212 men onboard (see NOU 1981: 11). The primary reason for this accident was failure of one of the main braces. Fatigue cracks had initiated at a hydrophone support that was welded into one of the main braces and had propagated further until it was so long that it finally fractured in a storm (see Figure I.1). The platform was designed without significant redundancy. Thus, the fracture of this

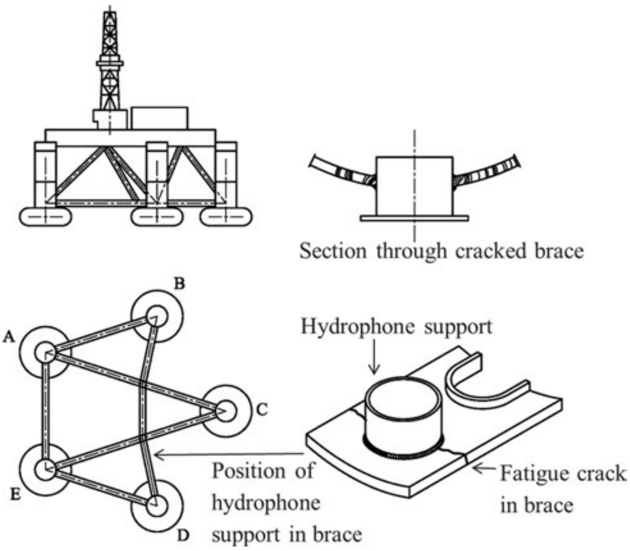

Figure I.1. Sketch of the *Alexander L. Kielland* platform with hydrophone support and fatigue crack into the main brace connecting column D to the structure (based on NOU 1981: 11).

brace resulted in failures in other elements, buoyancy was then lost, and the platform turned upside down; 123 men lost their lives. This accident resulted not only in greater research effort being directed toward fatigue of offshore structures but also in revised design standards with stricter requirements regarding documentation of redundancy and survivability of structures in unexpected situations. Please see Sections I.2.1, 5.5.6, and 16.3.2 for more details and assessments related to this incident.

In around 1975, high-strength steel was introduced into the fatigue design of ships. High-strength steel in ship fabrication is understood to refer to steel material with a nominal yield strength of around 315–350 MPa, while normal yield strength is approximately 235 MPa. Thus, the ultimate structural capacity of ships could be documented with use of less steel. The structural details remained similar to those for when normal steel was used, and upon which the design experience was based. This resulted in reduced section modulus of structural elements and increased stress ranges at the hot spot areas, especially in the side longitudinals. Significant fatigue cracking was reported until improved classification standards were developed; see, e.g., Yoneya et al. (1993) and Xu (1997).

Due to residual tensile stresses at welds, it has been normal practice in fatigue design of land and offshore structures to assume that the full stress range is providing the same fatigue damage independent of mean stress level. This means that all stress ranges are included in the design procedure as if they were producing tensile stress at the hot spot during the full load cycle. Until the 1990s, the fatigue design of sailing ships had to a large extent been based on experience, and in some way this had resulted in less required amount of steel than what could be documented based on the same fatigue analysis methodology as used for offshore structures. Thus, to avoid unnecessary increase in scantlings at details with a positive in-service experience without fatigue cracking, it was proposed to include a mean stress effect factor where the compressive part of the stress cycle is less damaging than a similar tensile stress range. Calibration of the fatigue analysis procedure with experience accounts for the mean stress effect and it also accounts for the uncertainty due to variable long-term loading, which has been difficult to fully assess and agree on.

During 2004 and 2005, new design rules for bulk carriers and oil tankers were proposed. These proposals were developed in two joint industry projects supported by different classification societies, and this resulted in two rather different analysis procedures for fatigue assessment (Lotsberg 2006a). Around 2009 it was decided by the International Association of Classification Societies (IACS) to harmonize these rules into one set of recommendations. This work was performed by the classification societies within IACS, and new common recommendations on fatigue assessment of bulk carriers and oil tankers accounting for residual stresses and mean stress effects were issued in 2013.

Long-term use of ship-shaped units permanently installed on the field require improved reliability with respect to corrosion and fatigue than a sailing ship that can be easier repaired. Thus, different recommendations on fatigue assessment of floating production vessels from that of ships have been developed the past 15 years.

As the offshore structures become older, the need for inspection and maintenance increases. Here inspection methods have been improved and probabilistic methods have been developed over the past 30 years to make the inspection planning more optimal, as explained in Chapter 18. Furthermore, it has been interesting to observe a significant development of Remote Operated Vehicles (ROVs) during the past 20 years. This has removed much of the need for using divers for underwater operations related to inspection and repair.

Development of new types of structures has lead to research in new areas. Fatigue strength of girth welds in tethers, risers pipes that also may be reeled, umbilical, and so forth are examples of this. At the end of the 1980s the need for high capacity connectors in tether strings such as shown in Figure 13.13 led to fatigue testing of high strength steel with yield strength larger than 500 MPa. This resulted in S-N curves for such material as shown in Section 4.1.5. Use of high strength steel forgings in riser systems and subsea wellheads has required further fatigue testing; reference is made to Wormsen et al. (2015) and additional S-N curves for this steel were included in DNVGL-RP-C203 (2016). Umbilicals are needed for subsea operations and fatigue testing of these has been performed in a number of projects, see also Section 4.1.11. Fatigue of flexible pipes used in the offshore industry is another item that has required research and development with respect to fatigue; see, for example, Fergestad et al. (2014). Research is also ongoing to improve the understanding between defects and fatigue strength in welded connections, which can be subject to high dynamic loads as explained in Section 4.6.2. Wind turbine structures placed in the sea is another example of new developments after year 2000 where a good fatigue design is required in order to resist long-term dynamic loading from wind, waves, and rotor motions.

Since the 1990s a number of papers have been published on improvement of welded connections using High Frequency Mechanical Impact (HFMI) treatment; see, for example, Statnikov (2004) and Kudryavtsev et al. (2004) for information on historic development. This is based on ultrasonic impact treatment resulting in less noise and vibration than by using standard hammer peening. However, here also some uncertainty on long-term improvement remains due to potential shakedown of beneficial compressive stresses at the hot spots due to variable loading; see also Section 11.7.8.

Research on development of new material, welding methods, and improvement of non-destructive methods is being performed. Also, development of numerical tools for analysis of residual stresses depending on materials and welding methods is an interesting but challenging research topic. Here a further developed analysis methodology may improve the basis for using more advanced analysis methods and taking actual fabrication methods and mean stress effects more into consideration in fatigue design of marine structures.

Thus, the understanding of fatigue has gradually improved over a long period, based on in-service experience, measurements of dynamic loads, laboratory fatigue testing, and theoretical considerations and analyses. However, the area is still significantly influenced by experience, and the fatigue capacity is dependent on a number of parameters that need to be assessed. There is still a need for analysis models that properly link these parameters together. Thus, based on history, it is expected that the need for significant research related to fatigue of structures will remain in the future. The history also shows that it is important that the engineers get a relevant education in fatigue assessment as the basis for design of reliable and optimal structures. It is also important that in-service experience from actual structures and learning from research and developments are transferred into design standards for fatigue assessment such that optimal and reliable structures can be designed and fabricated in the future. Since the 1980s a number of different standards for this purpose have been developed and maintained through revisions such as API RP 2A (2014), NORSOK N-006 (2015), ISO 19902 (2007), DNVGL-RP-C203 (2016), DNV-RP-C206 (2012), DNV CN 30.7 (2014), and IACS (2013); see also reference list for a more detailed description of these standards. During these years the safety philosophy has become better described. It should also be mentioned that the methodology for inspection planning for fatigue cracks during in-service life has been improved significantly since the beginning of the 1980s; see also Section 18.1 for a more detailed description of this development.

I.2 Examples of Fatigue Failures of Marine Structures

I.2.1 The *Alexander L. Kielland* Accident

The hydrophone support in the brace that failed in the *Alexander L. Kielland* accident was designed with a small double-sided fillet weld where the structural strength was significantly less than that of the main plate, as indicated in Figure I.2. Connections with local weak sections may show a brittle structural behavior when subjected to external loading, even if the material in the weld and the base material are ductile; see also Section 16.1. Fabrication of these connections may also be difficult as residual stresses resulting from the fabrication may lead to cracking due to deformation from temperature shrinkage. When the throat thickness is significantly smaller than the thickness of the plates, this deformation will likely be concentrated in the weakest part of the structure, which is the weld. The investigation report after the *Alexander L. Kielland* accident describes coating being observed in a 70 mm length on the inside fillet weld, showing that some cracking had already occurred during fabrication (see NOU 1981: 11). Further cracking of the fillet welds is reported to have been mainly due to overload of the static capacity of the welds until a crack pattern around a

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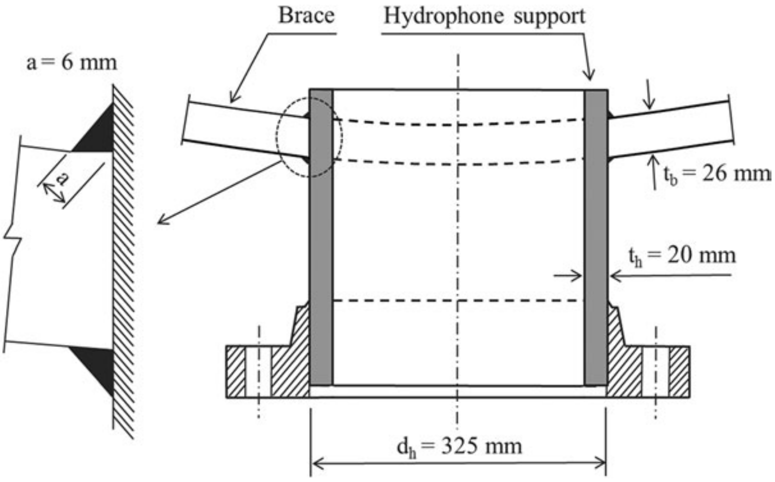

Figure I.2. Hydrophone support inserted in one of the main braces of the *Alexander L. Kielland* platform (based on NOU 1981: 11).

significant part of the circumference of the hydrophone support was reached. From this stage, further cracking into the main brace was by fatigue. At one side of the support a fatigue crack may have continued from the crack tip already present in the fillet weld. At the other side a fatigue crack may have initiated due to the large stresses at the hole when the fillet welds were cracked. The effective crack length was now already equal to the width of the hole, and the crack propagated rather fast. This crack growth is in agreement with calculated crack growth based on fracture mechanics in Section 16.3.2. An improved design methodology for tubular penetrating plates has been developed (see Section 5.5). Based on this methodology, it can be shown that the small fillet welds around the hydrophone support would also not have been adequate due to fatigue, even without the fabrication defects (see Section 5.5.6). A fatigue failure within a time period of less than four years can also be predicted using the analysis methodology available today, even without defects in the weld root. This accident demonstrated:

- that detailed and reliable fatigue analysis of offshore structures is needed;
- that requirements for robustness or damage tolerance in offshore structures in extreme situations are needed, and that the fatigue design criteria for marine structures should be dependent on consequence of a failure;
- that fatigue crack growth may initiate from items that are considered to be of minor importance for the ultimate load capacity;
- that fatigue cracks around a tubular section penetrating a plate result in large stress intensity as soon as the fillet welds are cracked around a significant part of the circumference; thus, the following crack rates correspond to a stress intensity for a crack length equal to the tubular diameter;
- that small welds with less structural strength than the base plate may show a brittle structural behavior, even if the material is ductile (see also Section 16.1);
- that the welding around a stiff and restrained section can be a challenge.

This accident showed that the design standards for offshore structures needed to be revised.