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SIGNIFICANCE AND APPLICABILITY OF STRUCTURAL INTEGRITY ASSESSMENT

ZNAČAJ I PRIMENLJIVOST OCENE INTEGRITETA KONSTRUKCIJA

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Abstract

To avoid unexpected and frequent serious failures of objects and equipment in service, and save their structural integrity, proper experimental and theoretical analyses are required, that are supported by modelling and numerical analysis. Structural failures in service have been experienced and can not be neglected. The developed procedures, based on fracture mechanics, enable to predict behaviour of a crack in a fracture process and to evaluate the safety and reliability of a structure under the applied loading in an operating environment. Regarding the significance of structural integrity, objects are classified into three groups. In the first group are objects made of stone, not sensitive to cracking, as are the preserved monuments of the ancient era. The second group includes objects prone to fracture from cracks: in this case structural integrity assessment is a requirement in order to prevent failure. In the third group are modern engineering achievements as are very large buildings (e.g. Burj Khalifa), and nano-sized objects. They both require, involving new aspects, the consideration of functionality and reliability, in addition to safety. Several examples are presented here and discussed for each group.

Izvod

Da bi se izbegli neočekivani i često ozbiljni otkazi u radu objekata i opreme i sačuvao integritet konstrukcija potrebne su odgovarajuće eksperimentalne i teorijske analize, podržane modeliranjem i numeričkom analizom. Mogućnost otkaza konstrukcije u radu se ne može zanemariti, jer se oni u praksi javljaju. Postupci, razvijeni na osnovu mehanike loma, omogućavaju da se predvidi ponašanje prsline u procesu loma i da se oceni sigurnost i pouzdanost konstrukcije pri opterećenju u radnim uslovima. Objekti su podeljeni u tri grupe s obzirom na značaj integriteta konstrukcije. U prvoj grupi su objekti, uglavnom izrađeni od kamena, koji nisu osetljivi na prsline, kao što su očuvani arheološki spomenici. Druga grupa uključuje konstrukcije sklone razvoju loma usled prslina: za njih se zahteva ocena integriteta da bi se sprečio otkaz. U trećoj grupi su nova tehnička dostignuća, kao što su velike građevine (na primer Burdž Kalifa) i objekti nano veličina. Zbog toga što se u oba slučaja unose novi aspekti, i objekti velikih i vrlo malih dimenzija zahtevaju da se, sem sigurnosti, razmotre funkcionalnost i pouzdanost. Za svaku grupu je nekoliko primera prikazano i diskutovano.

INTRODUCTION

The term “structural integrity” has been introduced for objects and structures prone to fracture to describe an important problem in the case of failure in service, sometimes with no warning, as is the case for welded structures, /1/.

On the other hand, many objects maintained their integrity during centuries and even millennia, but generally their originally intended use is no more actual. Today they represent valuable monuments and indicate historical development of civilisation. In many cases their integrity is intact and can be restored by only small interventions.

It is to say that structural integrity can be considered at a global and at a local level. Global structural integrity refers to an object or structure as a whole. The loss of structural integrity at global level means complete destruction of a structure that cannot be repaired, but also a damage that can be repaired after important redesign and reconstruction. The loss of structural integrity at a local level indicates local deterioration or crack occurrence that requires small repair, and in some cases, after proper structural integrity assessment the use of the structure can be permitted for specified time before repairing. Strict distinction between global and local structural integrity is not possible and is dependent on importance of object and failure risk.

In many cases experienced failure of objects is not explicable at the time of occurrence, requiring detailed and extended investigation, research and experimental analysis, /1/. It was also performed after successive serious failures of ships (Fig. 1) during the Second World War, /2/. It is revealed that the fracture of ships initiated from a crack, negligibly small compared to the size of the structure. These fractures had been simultaneously treated for several years in many institutes worldwide, whereas the problem was complex and required cooperation of scientists from all involved countries. The performed investigation can be considered as an initial step in the development of fracture mechanics.

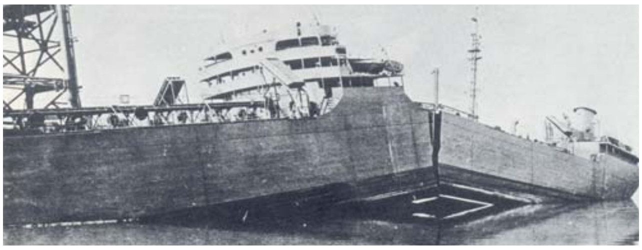

Figure 1. The “Schenectady” fractured amidships (1943), /2/.
Slika 1. Lom broda „Skenektedi“ po sredini (1943), /2/

Considering eleven different aspects of fracture, it became clear that the full answer to this complex problem can be given only after a series of full-scale laboratory tests. Following metallurgical aspects of the problem, step by step, the basic approach is defined by Boyd, /2/: “It would seem that the main factors which are under suspicion, namely welding, workmanship, design, locked up stresses (constrain) and even the quality of the material, have all been exonerated, and that the root of the trouble lies in an elusive property of the material, i.e. its Notch Sensitivity at Low Temperature” (unpublished report).

A following extended investigation and research was directed to cracks in a structure, enabling at the middle of last century to establish a new discipline, fracture mechanics. Fracture mechanics serves as the basis for structural integrity assessment.

Following the trace of cooperation in complex fracture problems, the European Group of Fracture (EGF) is established in the late sixties. According to EGF growing activities, the members have recognised that the term “fracture” in the title is too pessimistic, since the structures are not produced to be fractured. It is decided to rename EGF as the European Society for Structural Integrity (ESIS). The term “structural integrity” is accepted to define the condition in which the structure can be used in service reliably, regarding function and safety, even in the case of existing defects or damage. Just to mention that a crack is considered as the most critical defect in a structure.

Structural integrity assessment defines the significance of an existing crack in a structural component and all the actions that are to be taken to assure reliable operation. It is to say that George Irwin, who contributed strongly to the investigation of crack behaviour in theoretical, experimental and practical aspects, first called the new discipline “crack mechanics”, indicating its mathematical aspect. He changed it to “fracture mechanics”, since crack growth is really also considered in many other aspects, as in design, materials, standardization, testing.

Probably, the most precise definition of structural integrity is recently given by Steve Roberts as, “the science and technology of the margin between safety and disaster,” lending a huge amount of importance to structural integrity and responsibility upon the engineers who pursue it.

Structural integrity is an essential component of all structural engineering projects, both in mechanical and civil engineering, as these projects include bridges, buildings, dams, equipment, machines, devices, and complex systems, as power and process plants or district heating, including also new developed computers, nano structures and related products. Structural engineering encompasses the building or parts of equipment of large structures, and structural integrity largely refers to those objects’ soundness of design and construction, including workability and safety. For that it plays an important role in the daily grind of society, as well as in the safety of sometimes large populations of both humans and wildlife.

Two aspects of structural integrity require attention: the first is connected with the intended use and functionality, the second is the object size and its complexity. In that sense differences can be found in characteristics of constructed objects in classical civil and in mechanical engineering, and in now fast developing new information technologies, computer systems, micro- and nano structures.

The difference in structural behaviour can be characterised by many influencing factors. The first factor is design, depending on intended function and use. External effects follow (environment, loads). Material and manufacture of components also have an important influence.

The meaning of the term “structural integrity” requires additional explanation. The first reason is that a structure today, connected with integrity assessment, can be an object sized between 10^6 m (long pipelines), and 10^{-9} m (nanostructures). It is not possible to treat structural integrity in the same way in a so extended range. The second reason is that basic mathematical formulae for designing are derived for homogenous and uniform continua. They can be practically applied only as adopted by empirical coefficients. The third reason is structural materials and their properties, which can differ in many aspects. The selected material and manufacturing procedures have to be optimal for the structure and its intended use. Finally, the effects of loading and service conditions are important. Many structures are exposed only to gravity and environmental effects during use, which can last for centuries. Other objects can be prone to failure and require special treatment.

With this in mind, integrity refers to the quality of the structure to be whole and complete, ready for purpose, or in the unimpaired state. Structural integrity assessment is an approach to evaluate whether a structure is fit to withstand safely and reliably the loading and operating conditions throughout its expected lifetime.

In some cases knowledge is not sufficient to include specific situations and properties simply because they may not be predictable or are not experienced. This is the case with material property, as mentioned above.

Risk of possible failure of structures in service must be considered, especially when the consequence might be catastrophic and similar failures are already experienced. To avoid unexpected failures of equipment in exploitation and save their structural integrity for further use, the inspections, maintenance and repair are required and specified. Corresponding experimental and theoretical analyses are necessary, and measuring instruments, computer systems and software are to be included when appropriate, supported by modelling and numerical analysis. The lack of experience with new developed materials, structures and manufacturing procedures of new designed machines and devices dictates the necessity to apply additional analysis for safe service and integrity during the requested lifetime.

The aim of this article is to consider significance and applicability of structural integrity assessment, but also to discuss the imposed limitations. By introduction of fracture mechanics and damage mechanics as theoretical disciplines, and accepting that fracture most often leads to failure, integrity assessment is directed to crack growth analysis in various loading conditions and environments, as static overloading, fracture, fatigue, creep, corrosion and stress corrosion, and their possible mutual effects.

SIGNIFICANCE OF STRUCTURAL INTEGRITY ASSESSMENT

A historical preview of the development of engineering structures can help to get an impression on the significance of structural integrity assessment. For a long time objects are constructed regardless of operation life, in accordance with available knowledge, materials and experience. When more complex and sophisticated structures had been designed, following more and more strict requirements and applying materials of improved properties, using more improved technology, the failures became more and more important and solutions for extended operability were necessary. However, fast unpredictable progress in science and technology offers non-expectable capabilities in design and manufacture, but also, when required, new procedures on how to treat structural integrity and life.

It is to underline that this development has involved new serious problems, closely connected with environmental protection, from two essential reasons. The first is environmental pollution through the operation of industrial plants and all participating sectors in human community, like traffic. The second one is related to failures of pressurised equipment, often with catastrophic consequences. It became clear that knowledge and experience in the time of design and manufacture of machines and equipment were insufficient to satisfy all needs. The development of materials was behind the design requirements in many senses. The experience how to use new products in an economic, safe and reliable way was poor. One may claim that in spite of the huge progress of engineering, the situation is still similar to that from the early beginning of industrialisation, because each new development opened new problems, which could not be understood due to lack of knowledge. In this way a specific spiral in competition of knowledge and imagined design is created. Available knowledge enables realisation of colossal objects as huge buildings, large ships, airplanes of unbelievable size, thousands kilometres of long pipelines, and on the opposite size scale, microprocessors, nanostructures and related products, still under intensive development. But it is likely that there are no limits in knowledge and development. Although there is no end in the size of super large and super small products, on either side the necessary knowledge and skill must be under steady progress. Structural integrity is a common denominator for both classes, large and nano structures.

Examples of objects with global structural integrity saved for centuries have shown that small deterioration could be neglected or repaired. Also these objects can be restored in a convenient way or even redesigned if required, not affecting global structural integrity.

Several failure examples from service are presented and fracture as crack propagation is discussed, based on fracture mechanics approach. Developed procedures for structural integrity assessment in presented cases are capable to predict crack initiation and behaviour during fracture, e.g. to evaluate the reliability of the structure under the applied load in a different environment. This evaluation is based on a conservative model, convenient to cover possible uncertainties of different nature, but also to cover critical unexpected events. Case studies of experienced failures had to be followed by experimental tests, theoretical and numerical analysis. Sometimes previously unknown material properties /2/ and structures had to be additionally included in the analysis, and the structure had to be re-designed in order to improve its functionality, reliability and safety in service.

The significance of welded joints for the integrity assessment of structures is that they present the critical location. The shape of welding joint represents the source of stress concentration. And this is not the end with problems induced in welded joints. Different types of cracks can be formed in the welding procedure (crystallization, cold or reheating cracks, lamellar tearing). Additional problems are cracks that are not detected in inspection, and after some operating time they can initiate and grow by different mechanisms (corrosion, creep, fatigue, stress corrosion). The general intention to increase steel strength, in order to reduce the mass of the structure, is followed by reduced ductility and toughness, thus making crack occurrence in the heat-affected-zone (HAZ) a special problem, /1/.

To get an insight in structural integrity, several typical examples are selected and considered.

Preserved objects from the ancient age

Among numerous preserved very old objects, three examples are selected. They are typical in regards to structural integrity: preserved for centuries, and constructed for unlimited life. Joint characteristics of these objects are the structural material (stone) and that they were abandoned for different reasons, loosing also their intentional use. Today they serve as valuable historical monuments, attracting the attention of scientist and the public.

The Great pyramid of Giza (Khufu - Keops)

The Great pyramid of Giza (Cheops) /3/ is the only surviving of the Seven Wonders of the ancient era. Accompanied by several smaller pyramids, it is mostly intact in the global sense (Fig. 2)**.** The exterior of polished limestone is mostly removed by the Arabs to be used in the construction of mosques and other buildings. This gives a rough look of the pyramids. The original entrance, 16 meters high, is on the north side. Inside the pyramid of Cheops are burial chambers and four wells.

It is believed that these pyramids were built 4.5 thousand years ago and served as Egyptian pharaoh tombs. With its 146.6 m, the Great Pyramid was the tallest man-made structure in the world until 1889, when the Eiffel Tower was built. Today its height is 137 m, since it has lost some of its peak during time. The initial length of the pyramid side was 230.33 m, and is now reduced to 227 m. According to official estimates, the Great pyramid of Giza was built of 2.3 million stone blocks with an average weight of 2.5 tons. This means that the pyramid weighs about 5.750.000 tons. For construction, blocks lighter than 2 tons were used, and the heaviest blocks weighed 70 tons.

Figure 2. Great pyramid Cheops of Giza in the centre, /3/.
Slika 2. U sredini je velika Keopsova piramida u Gizi, /3/

The Great pyramid of Giza can be considered as an integral object, of slightly reduced dimensions after so long time and slightly damaged outer surfaces, constructed for unlimited life. It is exposed only to weight load and environmental effects, negligible to structural resistance. Effects of possible earthquakes or soil movement on the integrity are not noticed. It is restored by only small repairs (compared to the original size) during surveillance and maintenance.

Millions of tourists visit Giza to see the Great pyramid and the smaller pyramids.

Scientists are still surprised and can not explain yet how the Pyramids were built /4, 5/. How did ancient Egyptians pull 70 ton granite slabs up the Great Pyramid without the benefit of wheels? How did they carve granite with pure copper? Egyptologists have yet to explain how the tops of the Pyramids were built.

In the mid-1980s, Davidovits proposed that the pyramids were cast *in situ* using granular limestone aggregate and an alkali alumino-silicate-based binder, /4/. Following this proposal, Michael Barsoum from Drexel University, Philadelphia, USA, and his research team, using primarily scanning and transmission electron microscopy have investigated this possibility. Obtained results confirmed that this ancient concrete technology could be applied in pyramid construction, as presented in Fig. 3. There are still questions which need to be clarified, but the offered approach is promising also for explaining how the tops of the Pyramids were built.

Barsoum suggested that his study of 4500 year old rocks is not about the past, but more about the future.

Figure 3. Blocks that appear to have been cast (top); blocks most likely not cast (bottom).
Slika 3. Blokovi koji su verovatno liveni (gore) i blokovi koji najverovatnije nisu liveni (dole)

Parthenon /6/

The Parthenon (Fig. 4) is a temple in the Athenian Acropolis, Greece, dedicated to the Greek goddess Athena. It is constructed from 447 until 431 BC. It is an enduring symbol of Ancient Greece and one of the world's greatest cultural monuments. The Parthenon survived as a temple for a thousand years, till the 4th century AD, when Athens had been reduced to a provincial city of the Roman Empire. In the 5th century, the great cult image of Athena was moved to Constantinople, and later destroyed. In the 6th century, the Parthenon is converted into a Christian church (in Byzantine times the Church of Virgin Mary, in Latin occupation a Roman Catholic Church). In 1456, Athens fell to the Ottomans, and the Parthenon was converted into a mosque, with a minaret added. Its base and stairway are still functional, invisible from the outside. Otherwise, it was largely intact. In Venetian bombardment 1687, an Ottoman Turk ammunition dump inside the building exploded and damaged the Parthenon and its sculptures. In the 18th century some of the surviving sculptures were removed to European cities (London, Paris, Copenhagen).

The program of selective restoration and reconstruction to ensure the stability of the partially ruined structure of the Parthenon is being carried out. The Parthenon will not be restored to a pre-1687 state, but the explosion damage will be mitigated as much as possible, to restore the structural integrity of the edifice (important in this earthquake-prone region) and the aesthetic integrity by filling in chipped sections of column drums and lintels, using precisely sculpted marble cemented in place as in the original, supported as needed by modern materials. Today, most of the Parthenon marble remains are in Athens in the new Acropolis Museum, opened on June 20, 2009.

Figure 4. Parthenon, /6/.
Slika 4. Partenon, /6/

In regards to the preserved structural integrity of the Parthenon, several comments are necessary. It is built of stone, material which can sustain millennia for intended purposes. The structural integrity required for its altered purposes has been preserved also, after reconstructions undertaken.

Now the Parthenon is a valuable historical evidence of human civilisation development, with adopted structural integrity for intended purpose after a recently performed reconstruction.

Leptis Magna, /7/

The Leptis Magna was a prominent city of the Roman Empire. Its ruins are located on the coast in Libya, 130 km east of Tripolis. The site is one of the most spectacular and unspoiled of Roman ruins. Although founded around 1100 BC by Phoenicians, it became prominent in the Carthage period (4th century BC). After 50 years as an independent city, in 146 BC it became part of the Roman Republic. Under emperor Septimius Severus, in 193 BC, Leptis Magna became, as a major trading post, the third-most important city in Africa, after Carthage and Alexandria. Severus had created a magnificent forum and rebuilt the docks. The natural harbour had a tendency to silt up, but the changes had worsened this. The eastern wharves are well preserved, since they were hardly used. In 439, Leptis fell under the control of the Vandals and their king, Gaiseric, made it his capital. He demolished the city's walls so as to dissuade its people from rebelling against Vandal rule. In 523 a group of Berber raiders sacked the city. In 534 Belisarius destroyed the kingdom of the Vandals and Leptis became a provincial capital of the Byzantine Empire, but has never recovered from the destruction. By the time of the Arab conquest of Tripolitania in the 650s, the city was abandoned except for a Byzantine garrison force.

Figure 5. Theatre in Leptis Magna, /7/.
Slika 5. Amfiteatar, Leptis Magna, /7/

While the Great Pyramid and Parthenon are individual objects and only historical monuments today, the theatre in Leptis Magna gives out an impression that it just waits for an audience for the next performance. Now Leptis Magna (Fig. 5) is declared as a World Heritage Site (Fig. 6).

Figure 6. Leptis Magna in preserved state is a World Heritage Site
Slika 6. Leptis Magna u sačuvanom obliku je svetska baština

Bridges

Three different studies about bridges are presented.

The first is the I-35W Mississippi River bridge (Bridge 9340), designed and constructed according to strict requirements, and opened in 1967, failed in 2007 /8, 9/. This catastrophic failure, and other similar failures, indicate how structural integrity assessment is significant for bridges.

Figure 7a. The bridge before the collapse, /10/.
Slika 7a. Most pre kolapsa, /10/

The bridge (Fig. 7a) was an eight-lane, steel truss arch bridge that carried Interstate 35W across the Mississippi River in Minneapolis, Minnesota, USA. On August 1, 2007, during the evening rush hour, it suddenly collapsed, killing 13 people and injuring 145. The bridge, carrying 140 000 vehicles daily, was Minnesota's fifth busiest. The National Transportation Safety Board (NTSB) cited a design flaw as the likely cause of the collapse, and asserted that additional weight on the bridge at the time of collapse contributed to catastrophic failure (Fig. 7b).

Figure 7b. The collapsed bridge, 1st August 2007, /10/.
Slika 7b. Srušen most, 1. avgusta 2007, /10/

Some facts should be mentioned here. On December 19, 1985, the temperature reached –34°C. Cars coming across the bridge experienced black ice and there was a massive pile up on the northbound side of the bridge.

In February and in December 1996, the bridge was identified as the single most treacherous cold-weather spot in the Twin Cities freeway system, because of the almost frictionless thin layer of black ice that regularly formed when temperatures dropped to –1°C and below. The bridge's proximity to Saint Anthony Falls contributed significantly to the icing problem and the site was noted for frequent spinouts and collisions. By January 1999, Mn/DOT began testing magnesium chloride solutions and a mixture of magnesium chloride and a corn-processing by product to reduce the black ice that appeared on the bridge during the winter months. In October 1999, the state embedded temperature-activated nozzles into the bridge deck to spray the bridge with potassium acetate solution to keep it free of winter black ice. The system came into operation in 2000. It has been raised as a possibility that the potassium acetate may have contributed to the collapse of the 35W bridge.

Immediately after the collapse, help came from the Minneapolis-Saint Paul metropolitan area, and a response from personnel, charities, and volunteers. Within a few days of the collapse, the Minnesota Department of Transportation planned a replacement bridge, the I-35W Saint Anthony Falls Bridge. Construction completed rapidly and it opened on September 18, 2008.

Two of the following examples are old bridges with preserved integrity.

The Iron Bridge, /10/, crosses the River Severn at the Ironbridge Gorge in Shropshire, England (Fig. 8).

It was the first arch bridge in the world to be made out of cast iron, a material which was previously far too expensive to be used for large structures. However, a new blast furnace nearby lowered the cost and so encouraged local engineers to solve an important problem of crossing the river, and replacing the ferry by a reliable crossing.

Figure 8. The Iron Bridge (top), crack and repairs in bridge (centre) and cracked supports (bottom).
Slika 8. Gvozdeni most (gore), popravka prsline na mostu (sredina) i oslonci sa prslinom (dole)

In 1773, Thomas Farnolls Pritchard suggested to build a bridge out of cast iron. By 1775, after Pritchard had finalised the plans, Abraham Darby III, an ironmaster from Coalbrookdale, was commissioned to cast and build the bridge. The bridge was opened on January 1st, 1781.

The method chosen to create the structure was based on carpentry. Each member of the frame was cast separately, and fastenings followed those used in woodworking, as the mortise and tenon and blind dovetail joints. Bolts were used to fasten the half-ribs together at the crown of the arch. Large parts were needed to create a structure to span 30.5 m rising to 60 m above the river. The largest parts were the half-ribs, each about 21 m in length and weighing 5.25 tons. The bridge comprises about 800 castings of 12 types.

Just a few years after the construction of the bridge, cracks appeared in the masonry abutments, caused by ground movement. Some of the present-day cracks in the cast iron may date from this time, although others are probably casting cracks. Some were pinned with wrought iron straps, but others have been left free. By 1802, the southern stone abutment had to be demolished, and replaced with temporary wooden arches, before eventually being replaced by iron arches. Many of the cracks visible today in the bridge have been left untouched, however. The bridge was over-designed, and subsequent bridges built by Thomas Telford, used much less cast iron. His cast iron arch bridge at Buildwas used less than half the weight for a greater span (39.6 m). However, it suffered similar problems of abutment movement and was replaced in 1902. The cast iron bridge at Coalport, built in 1818, is even more impressive because of its lean, streamlined design, and it still carries vehicular traffic. It has about half the weight of cast iron and is longer than the earlier iron bridge structure. It was renovated in 2004.

In 1972 a programme of major repairs took place on the foundations. It involved creating a ferro-concrete counter-arch under the river. In 1999-2000, the Iron Bridge was renovated again, with replacement of cast iron road plates with steel plates, and a lightweight top surface. While the smaller parts were cast using wooden patterns, the large ribs were cast freely in excavated moulds in casting sand.

The bridge was barred to vehicular traffic in 1934.

The Ironbridge and town, is a tourist attraction, part of the UNESCO Ironbridge Gorge World Heritage Site.

The Mehmed Paša Sokolović Bridge, /11/, is a bridge in Višegrad, over the Drina River (Fig. 9) in eastern Bosnia and Herzegovina. It was completed in 1577 by the Ottoman court architect Mimar Sinan on the order of the Grand Vizier Mehmed Paša Sokolović, of Serbian origin. UNESCO included the facility in its 2007 World Heritage List.

Figure 9. Mehmed Paša Sokolović Bridge - The Bridge on the Drina
Slika 9. Most Mehmed Paše Sokolovića – Na Drini ćuprija

A characteristic of the apogee of Ottoman monumental architecture and civil engineering, the bridge has 11 masonry arches with spans of 11 to 15 m, and an access ramp at right angles with four arches on the left bank of the river. The 179.5 m bridge is a representative masterpiece of Sinan, one of the greatest architects and engineers of the classical Ottoman period. The unique elegance of proportion and monumental nobility of the whole site bear witness to the greatness of this style of architecture.

The universal value of the bridge at Višegrad is unquestionable for all the historical reasons and in view of architectural values it has. It represents a major stage in the history of civil engineering and bridge architecture.

The bridge particularly bears witness to the transmission and adaptation of techniques in the course of a long historical process, but also to important cultural mixtures of different civilizations. Its symbolic role has been important through the course of history, and particularly in the many conflicts that took place in the 20th century.

Its cultural value transcends both national and cultural borders. Located in a position of geostrategic importance, the bridge bears witness to important cultural exchanges between the Balkans, the Ottoman Empire and the Mediterranean world, between Christianity and Islam, through the long course of history up to this day. The management of the bridge and repairs had also involved different political and cultural powers: after the Ottomans came the Austro-Hungarians, then Yugoslavia, and the Republic Srpska, a part of Bosnia and Herzegovina.

The property, principally consisting of the bridge, the access ramp and the two river banks up- and downstream, are protected by its buffer zone on each bank of the Drina river. The Drina is a mountain river, collecting water from the mountains of the Balkans towards the Sava and Danube Rivers. It is prone to flooding and the bridge parapets were destroyed in a heavy flood in 1896. The integrity of the bridge is vulnerable but is now adequately protected by the buffer zone and appropriately expresses the values it embodies.

The bridge underwent several periods of restoration and reconstruction in 1664, 1875 and 1911. Between 1914 and 1915, three of the western arches were destroyed. They were rebuilt by 1940. During World War II another five arches were ruined in the same area of the bridge. These were reconstructed by 1951. At this time, the stone paving was also renewed with electric cables installed underneath.

The bridge is famous for its beauty, as well as for the Nobel Prize in Literature, in 1961 given to Ivo Andrić for his celebrated novel “The Bridge on the Drina”. Andrić wrote the novel while living quietly in Belgrade under German occupation during World War II, and published it in 1945. The novel covers the time period of about four centuries.

The historical bridge has also witnessed mass executions during the 1992-1995 of the inter-ethnic Bosnian conflict.

Despite these historical events, authenticity has generally been maintained through the course of the bridge’s successive restorations. More recently, the structure is declared in danger of collapse due to fluctuations in the river level caused by a hydroelectric dam built upstream, one in Bosnia and one in Serbia, that affect the river water levels, and damage from the vibration of vehicles passing over the bridge. A bi-national working group to analyse the impact of power generation operations on the river is formed in order to preserve the bridge. The bridge is barred to vehicular traffic some years ago, serving only for pedestrians.

Eiffel Tower, /12/

The Eiffel Tower, a very special civil engineering structure, still attracts the attention regarding structural integrity.

The Eiffel Tower (Fig. 10), nickname ‘La dame de fer’ - *The iron woman*, is a 1889 iron tower located on the Champ de Mars in Paris, that has become both a global icon of France and one of the most known structures in the world;

millions of people ascend it every year. Named after its designer, Gustave Eiffel, the tower was built as the entrance arch for the 1889 World Exhibition. The tower is 324 m tall, the tallest constructed civil engineering object in the world until 1930. The tower has three levels for visitors. It is possible to ascend by stairs or lift to the first and second levels. The walk to the first level is over 300 steps, as well to the second level, other levels are accessible only by lift.

Figure 10. Eiffel Tower, /12/.
Slika 10. Ajfelova kula, /12/

The metal structure of the Eiffel Tower weighs 7 300 t, while the entire structure including non-metal components is 10 000 t. Depending on ambient temperature, the top of the tower may shift up to 18 cm because of thermal expansion of the metal on the side facing the sun. It may sway in the wind up to 6-7 cm without making an impact on its structural integrity.

At the time the tower was built many people were shocked by its daring shape. Eiffel was criticized for the design and accused of trying to create something artistic, or inartistic according to the viewer, without regard to engineering. This amazing structure was only supposed to be temporary and dismantled twenty years later, in 1909. It was not removed, due to the fact that it became valuable to communication, with radio and television stations using the massive tower for broadcast.

Eiffel and his engineers, however, as experienced bridge builders, understood the importance of wind forces and knew that if they were going to build the tallest structure in the world they had to be certain it would withstand the wind, i.e. to save the structural integrity. Eiffel said: "Now to what phenomenon did I give primary concern in designing the Tower? It was wind resistance. Well then! I hold that the curvature of the monument's four outer edges, which is as mathematical calculation dictated it should be. It will give a great impression of strength and beauty, for it will reveal to the eyes of the observer the boldness of the design as a whole." The shape of the tower was determined by empirical methods accounting for the effects of wind, and graphical methods, without an overall mathematical framework.

In the descriptive book "The 300 meter tower" Eiffel gave indications of his calculations. Careful examination of the tower shows an exponential shape, in two steps: (1) a base, which is a sort of bar stool, very sturdy, standing on 4 main pillars, bonded and extended with a lighter batter at the smaller level as the second floor (Fig. 10), (2) a tower firmly attached atop.

The value of the pillar base is directly related to the swaying caused by wind forces. The greatest difficulty in erecting it was the bonding of the four main pillars at the first floor. With the available equipment of the period, it was necessary to implant as precisely as possible four bases 80 meters apart from each other and then to raise the four pillars at a slant and to prop them in millimetre precision fifty meters above ground. The erection of the pillars, auto-stable, above the first floor was less difficult. As for the tower, it was erected with less difficulty, apart from working at heights. Two apparent sections where in tension: the horizontal connections on the first floor (7-meter wide girders), the base of the tower top.

The structure was made of puddle iron, and not steel. The Tower was assembled using a limited number of fabricated parts, and several other cast iron parts including 16 truss supports, connecting the masonry and the structure.

The rivets were high quality that of boiler rivets.

Many explanations are proposed over the years; the most recent is a nonlinear integral equation based on counterbalancing the wind pressure on any point on the tower with the tension between the construction elements at that point.

The Eiffel Tower is not all the same colour. In the regular maintenance, since the iron still rusts, it is painted with 50-60 tons of paint every 7 years in 3 different, but similar colours, with the darkest being at the bottom. Every so often, the colour itself has changed, with a poll taking place on the lower level for which colour it should become, /13/.

While everyone alive is aware of the Eiffel Tower, many are unaware that the tower today is not the tower built in 1889, containing 18 000 pieces of iron. Those pieces were joined together with 2.5 million rivets, and the structure is nothing but a big frame. To save the tower's integrity it is necessary to perform regular maintenance, consisting of inspection and repair procedures, some parts need to be removed and replaced with new pieces. There are some data that about 300 repairs had been performed annually, indicating that the initial 18 000 pieces had been replaced two times by now.

According to the official Eiffel Tower website /12, 13/, actions to improve the design and structural integrity had been performed. In that sense, in the 80s, a very ambitious program of renovation was launched. The Tower structure was given a thorough examination, strengthened in certain locations and lightened in others with the removal of 1 340 tons of material that had been added over the years. Safety standards were redefined and adapted to modern requirements, particularly where they concerned fire safety. The third level elevator was replaced, as was the old spiral staircase. This ongoing maintenance is intended to keep the Tower in excellent condition: special care is given to the monitoring of change, relying on the latest techniques available so as to prevent any possible deterioration. This process helps give the Tower a very long life expectancy.

The Eiffel Tower is an impressive proof that the integrity of complex metallic structures can be assured and saved. However, the necessity of proper inspection, maintenance and repair in this case is recognised and required measures are applied.

Transportation means

Transportation means are designed and produced for use on water (ships and boats), on the ground (automotive vehicles, trains), in the air (airplanes, helicopters) and in space (shuttles, rockets). To achieve their purpose, to move from one location to the other, they have to be driven, that means to be exposed to dynamic forces. Hence, the design and structure of transportation means are complex and sophisticated. Movement and complex structures make them prone to failure. On the other hand, the production of transportation means in the world is tremendous, and one of the first requirements is the safety in exploitation and guaranteed structural integrity. For example, yearly production of passenger cars in 2010 was about 58 million and only products of high reliability will be accepted on the market. The best producers offer today long guaranteed term, even without time limited conditionally, e.g. Opel. This is a consequence of available knowledge, gained experience, successful modelling and experiments and induced codes, standards and recommendations in design, manufacturing and maintenance. Much more strict regulations are prescribed and accepted in the airplane industry, assuring minimal level of failures, usually due to unexpected and unpredictable flight conditions. However, aircraft failures took place /14/, requiring a followed analysis, consideration and improvements in system /15, 16/. Generally, one can state that structural integrity for aircraft and passenger is at the highest level. One of the reasons for that is the continuous investigation and research of fatigue, most frequent mode of failures of complex machines and devices, /17/.

The story about fatigue started in 1837, /17/. The term "fatigue" is introduced by Poncelet describing metals as being *tired* under variable dynamic loading in his lectures at the Military School at Metz. But fundamental investigation followed after the "Railroad Catastrophe at Meudon" in France, /18/. The train returning to Paris from Versailles crashed in 1842 (Fig. 11) after the locomotive broke an axle (Fig. 12). The carriages behind piled into the wrecked engines and caught fire. At least 55 passengers were killed trapped in the carriages. The accident was witnessed by J. Locke, the famous British locomotive engineer, and widely reported in Britain. Rankine's investigation of broken axles in Britain highlighted the importance of stress concentration, and the mechanism of crack growth with repeated loading. His and other papers suggesting a crack growth mechanism through repeated stress were ignored, and fatigue failures occurred at an ever increasing rate on the expanding railway system. Other and spurious theories seemed to be more acceptable, such as the idea that the metal had somehow "crystallized." The notion was based on the crystalline appearance of the fast fracture region of the cracked surface, but ignored the fact that the metal was already highly crystalline.

Figure 11. Versailles train disaster, /18/.
Slika 11. Katastrofa voza iz Versaja, /18/

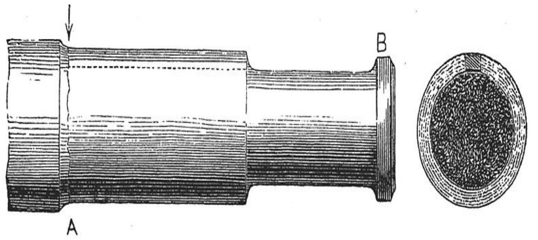

Figure 12. Drawing of a fatigue failure in an axle (1843).
Slika 12. Crtež preloma zamornog loma osovine (1843)

Wöhler summarized his long experimental work on railroad axles in 1870. He concludes that the cyclic stress range is more important than the peak stress and introduced the concept of endurance limit. In high-cycle fatigue situations, material performance is commonly characterized by an *S-N* curve (Wöhler curve). This is a graph of the magnitude of a cyclic stress, *S*, against the logarithmic scale of cycles to failure, *N*. In almost the same form it is used even today, but also in many modified forms. It is to mention here that a complete explanation of fatigue is still missing and fatigue control in structures, including airplanes and cars is based on gathered experience and experimental data. Today, the generally accepted in practice Paris law is based on experimental data and contains many simplifications.

Boilers and pressure equipment

Pressure equipment represent an important part in modern life and production. They are used in processing plants, refineries, power plants, but also they are applied as components of machines and devices. In everyday life and in domestic use they cannot be avoided, let us mention just boilers and gas containers in households. Basic components in pressure systems are pressure vessels and pipelines, exposed to inner pressure. In addition to inner pressure, boilers are exposed to heat effects. Operating in severe conditions, pressurised components fail frequently, and thus structural integrity assessment is one of basic requirements for their use. There are too many examples of pressure equipment failures, often followed by explosion and catastrophic consequences.

The list of boiler and pressure vessel failures is pretty long, including those that ended with an explosion, /19/. Hewison /20/ reported the list of 137 British boiler explosions between 1815 and 1962: 122 were in the 19th century and only 15 in the 20th century. This can be taken as an indication that all pressure equipment are prone, even today, to failure. Hence, safety of pressurised equipment is a substantial requirement for service, and strict measures are taken, starting from design, through manufacture, inspection and maintenance, in order to assure and prove necessary quality levels as a pre-condition of controlled and reliable service. In spite of all measures undertaken, failures of pressurised equipment still occurred.

Here, two typical cases of storage tank failures are presented /21/, just to indicate some basic problems which can be met in fracture analysis. Similar problems are also important in structural integrity assessment. The cases are pretty simple since only the vessels were damaged. In the first case (I) fracture is brittle (Fig. 13), in the second (II) it ended by plastic collapse (Fig. 14). The fracture mode is quite different, although used steels were of the same class, 8 mm thick, the fracture mode was different due to different loading conditions.

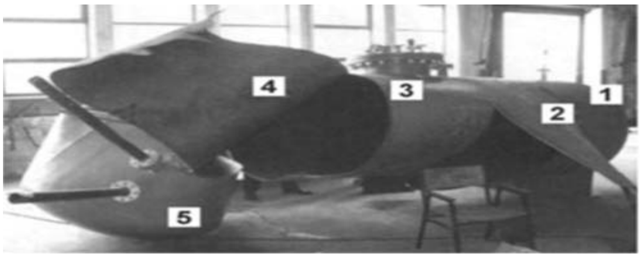

Figure 13. Brittle fracture of the underground storage tank (I), /21/
Slika 13. Krti lom podzemnog rezervoara (I), /21/

Figure 14. Plastic collapse of transportable storage tank (II), /21/
Slika 14. Plastični lom transportne cisterne (II), /21/

The failure of vessel I – underground storage tank for liquefied natural gas, 9.96 m^3 in volume, made of structural steel S355J2G3, occurred due to brittle fracture at proof pressure test for acceptance. The lowest working temperature of the storage tank is –20°C, and maximum operating pressure 16.7 bar. The requirements for vessel acceptance (parent metal properties, ultrasonic testing and radiographic examination of welded joints) had been met. The proof pressure was 25 bar, and required testing temperature must be at least 25°C higher than nil-ductility transition temperature. Transition temperature for the applied steel is –20°C, so proof pressure testing should be performed above +5°C, in order to be above transition temperature. In this test, liquefied nitrogen is brought from a special storage tank where it was kept at –196°C.

An explosion occurred in this test, and the tested tank was destroyed by brittle fracture, attributed to a temperature lower than transition temperature due to gas expansion. The crack initiated in coarse microstructure of HAZ, prone to brittle behaviour, in the circumferential weld final bead, in the lower part of vessel mantle, since there the temperature is lower. Stress concentration in the welded joint is expected, so crack initiation and brittle fracture in the plane strain condition in these tests might occur. Reaching the region of higher toughness, the crack deviated and arrested in the parent metal. On the other side, the crack propagated longitudinally through the parent metal. Analysis revealed a flat fracture surface, perpendicular to the plate surface on both sides of the initiation point along HAZ, as typical for brittle fracture. The crack propagated in an unstable manner parallel to vessel longitudinal axis, by crack driving force corresponding to maximal stress, i.e. by hoop stress. After some time the vessel temperature increased, and continued crack propagation was stable by ductile fracture mechanism with fracture surfaces at an angle of 45°, in the plane stress condition. The fracture of tested storage tank is a typical example how the welded structure of expected ductile behaviour in a given loading condition can be fractured in a brittle manner.

The second failure refers to the mobile storage tank (II), made of microalloyed steel, 4 m^3 in volume, for liquefied ammonia (NH_3) transport. Design pressure was $p = 16$ bar and temperature $t = 5$°C, following the requirements for hazardous fluid transportation. The tank failed after 18 years of service. In the critical situation the tank was charged with 320 kg of ammonia above the allowed 2120 kg. Due to the increase of environment temperature to 23.7°C during transport, the pressure of gas in the vessel increased, causing plastic deformation, bulging, local wall thickness reduction, and final fracture by plastic collapse after explosion. In vessel II the crack initiated in the HAZ of the fillet weld, between the mantle and support holder, from undercut 1 mm deep, visible on the fractured surface. In the region of constrained plastic deformation (plane strain), the crack grew longitudinally first, and then in the direction perpendicular to the vessel axis, Fig. 14. The crack then propagated through the parent metal and circumferential weld in the hoop stress direction, with ductile fracture appearance. Scanning electron microscopy revealed the fibrous ductile fracture, and through the thickness semi-elliptic crack growth. Shear lips are typical here, and the fracture surface is inclined by 45°, in the direction of maximum shear stress. Wall thickness was reduced to 5.3 mm at the point of crack initiation.

In the design, the wall thickness for both vessels was determined based on yield strength, for both steels of value corresponding to specification and safety margins. This is a general approach to structural integrity regarding the strength, but the integrity in service can be assured only if all rules are obeyed. In case of vessel I, the testing temperature, due to misuse was lower than the requested, enabling brittle fracture to initiate. In the case of vessel II, the imperfection as the 1 mm deep undercut had not been detected at inspection.

Presented cases are very simple and the failures could be avoided. More care and attention is necessary for thick-walled pressure equipment, /1/. For considered spherical storage tanks /1, 22, 23/ due to possible brittle fracture, the approach leak-before-break (LBB) can be recommended.

The above presented text probably did not show how significant the structural integrity assessment of pressure equipment might be. To complete the picture it is to recall the Bhopal great disaster, /24/. The 1985 reports give a picture of what led to the disaster and how it developed, although they differ in details. Factors leading to the gas leak included:

1. Use of hazardous chemicals - methyl isocyanate (MIC) instead of less dangerous ones.
2. Storing these chemicals in large tanks instead of over 200 steel drums.
3. Possible corroding material in pipelines.
4. Poor maintenance after the plant ceased production in the early 1980s.
5. Failure of several safety systems (due to poor maintenance and regulations).
6. Safety systems being switched off to save money, including the MIC tank refrigeration system which alone would have prevented the disaster.

The items 1, 2 and 6 refer to the Bhopal plant, and in general sense indicate insufficient management care. Items 3; 4 and 5 are in direct context with the presented paper.

Collapse of heavy machinery – bucket wheel excavator

Collapse of bucket wheel excavator (Fig. 15) in an open surface coal mine was caused by the fracture of lugs on the counterweight holder (Fig. 16).

Figure 15. Collapse of bucket wheel excavator, /1/.
Slika 15. Kolaps rotacionog bagera, /1/

Some details of combined fracture are given in Fig. 17.

Cracks that initiated from defects in T welded joint, between the lug and web (a, c), had grown by variable loading as fatigue cracks on both sites of front lug plate. On the back side, fracture was only brittle (b). At the end of the fatigue crack, stable crack growth in plane stress condition started after blunting of the fatigue crack tip and reached the final stretch zone (d). On one side the final stretch zone in position ZP (a) developed before final brittle fracture. On the other side, position CA, (a, c), the stretch zone partly developed after crack blunting, and after stress redistribution, the crack continued to grow again in a stable manner (e) up to the final stretch zone (a), followed by fast fracture. When the cross section area of lug plate was reduced to one third, the excavator collapsed.

Figure 16. Fracture of two lugs on the counterweight holder caused the collapse of rotor excavator, /1/.
Slika 16. Lom dve uške držača protivtega izazvao je kolaps rotacionog bagera, /1/

Fatigue fracture initiated in the fusion zone between two beads. Ratchet marks were completely in the weld metal, with stress concentration due to geometry and weld metal overfill. Two initial fatigue cracks formed one dominant crack. On the opposite side of weld metal there is the lack of penetration in the same weld region. Microstructural heterogeneity at the border between two passes and residual slag had been detected at the location of crack initiation. The collapse of the wheel excavator is explained based on experience from previously performed case studies, /1/.

One can expect the occurrence of initial cracks in the welded joint, fatigue crack growth under variable loading, continued stable crack growth in the ductile material and final fracture of the reduced cross-section due to overloading. To explain this collapse, acting influencing factors have to be analysed.

The first one is the external load. The working load in open mines is variable and random. In the design, this is taken into account through corresponding rules and directives.

The second important influence is the quality level of manufactured welded joints. According to performed investigation this could be a weak point, responsible for collapse. Probably, the necessary quality level had not been achieved, in regard to manufacture and inspection, indicating that requirements for quality assurance were not fulfilled.

In-service inspection and maintenance is the third influencing factor. Even in the case that in the acceptance process of the structure, all requirements are fulfilled, it is a question why periodical inspection during service did not prescribe more detailed NDT of critical welding joints and lug plates. There was sufficient time to repair the structure during the crack growth period, if the crack had been detected.

It is not difficult to conclude that ISO 9000 standards were not respected in this case, meaning standards ISO 3834, EN 287 and EN 288 were not properly applied, and, probably the required independent inspection did not verify NDT results. Hence, the poor quality of welded joints might be considered as the origin of this failure.

Less significant, but a frequent problem is everyday repair of equipment /25, 26/. Some features of this problem are worth to be accentuated.

1. Imperfections due to design and manufacture
2. Final proof of quality before putting into service
3. Properly defined inspection, maintenance and repair
4. Qualification and certification of personnel

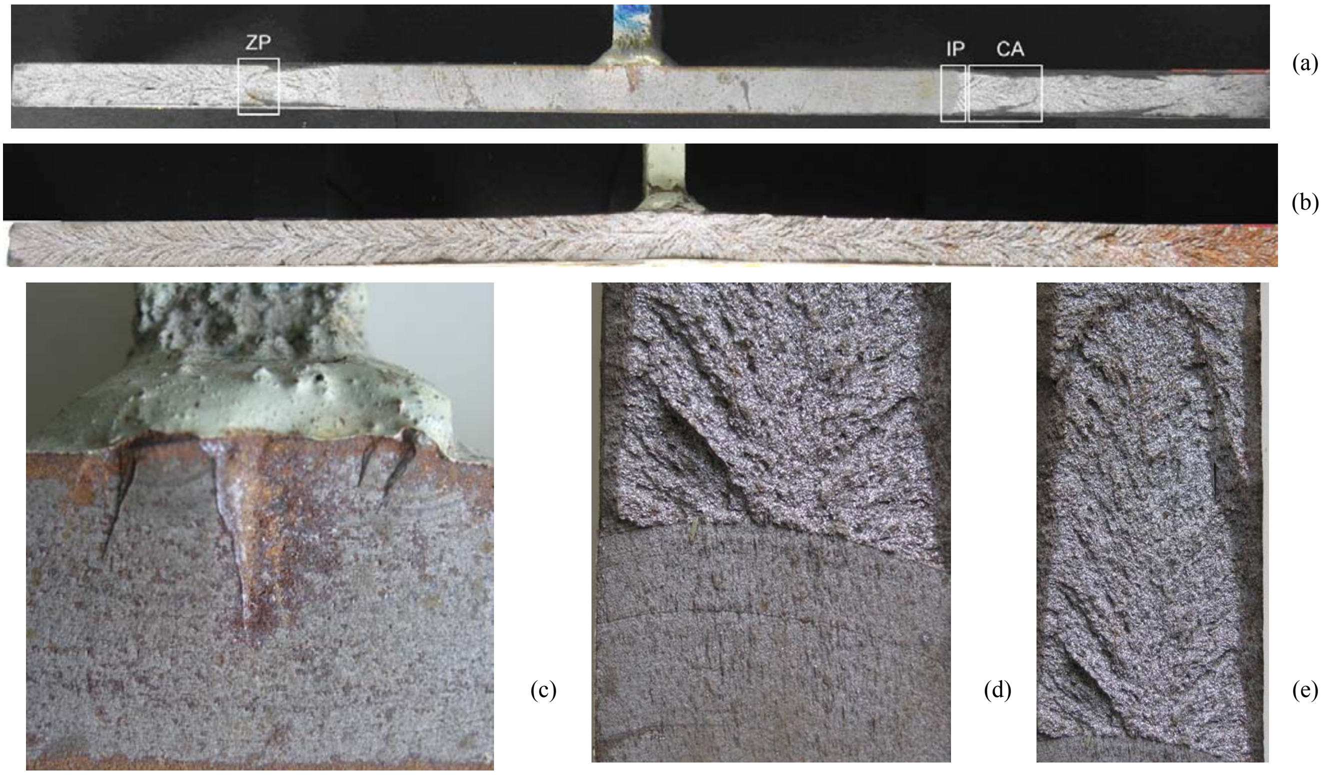

Figure 17. (a) Combined fracture (fatigue, stable crack growth with shear lips and final failure) of lug upper part
(b) Brittle fracture of lug lower part, indicating single initiating points from both sites
(c) Enlarged view of T welded joint – marked development of initial (1) and final fatigue cracks (2)
(d) Extension of fatigue and stable crack with shear lips (IP) (e) Crack growth till formation of first final stretch zone (CA), /1/.
Slika 17. (a) Kombinovani lom (zamor, stabilni rast prsline sa usnama klizanja i konačni lom) gornjeg dela uške
(b) Krti lom donjeg dela uške, u kome se vidi područje zajedničkog početka loma
(c) Uvećani izgled T zavarenog spoja – označen razvoj početnih (1) i konačnih (2) zamornih prslina
(d) Zamorna prslina i stabilni rast prsline sa usnama klizanja (IP) (e) Rast prsline do stvaranja prve zone konačnog razvlačenja (CA), /1/

Failure of rotary equipment – fracture of turbine blades

Rotary equipment is exposed to variable loading that can produce fatigue of material, and to hostile environment that can produce corrosion. Steam turbine blades might be exposed to both effects. In such cases, fracture of blades can be the cause of catastrophic turbine failure, /27/. How the problem with blades is complex one can conclude from the percentage of different factors of blade failures:

- Unknown 26%
- Stress-corrosion cracking 22%
- High-cycle fatigue 20%
- Corrosion-fatigue cracking 7%
- Temperature creep rupture 6%
- Low-cycle fatigue 5%
- Corrosion 4%
- Other causes 10%.

In the presented case of the 300 MW turbine, the power plant was operating at full capacity until the accident. Suddenly, abnormal sound was heard, followed by intensive shock, explosion and crashing, and ended with a fire. The fractured pieces went through the building wall. Serious direct and indirect expenses followed this failure. By applying the principles of structural integrity assessment it was possible to prevent the failure. Several activities are necessary. First of all – to detect and define defects, cracks as most important, which can affect the service of structure. Most effective is the non-destructive inspection by sophisticated procedures. Not only the location and size, but also the severity of damage must be recognized.

Turbine failure was attributed to simultaneous fracture of three blades at different locations in one flux of the low pressure turbine. Two blades were fractured in the root, and the next one 40 mm above the root. Blade fractures produced turbine imbalance and caused an overloading, which could not be sustained by the rotor shaft.

The initial fatigue crack in one blade was 1100 mm^2 or 14% of cross section area (Fig. 18), and final fracture was fast, but ductile. The stretch zone can be recognised at the fatigue crack front. After produced imbalance by fracture of the first blade, the initial fatigue crack of 280 mm^2 or 4% of cross section in the next blade was sufficient for fracture (Fig. 19). Then the third blade broke by overloading (Fig. 20). Three blades in another flux also failed.

A crack in one of the blades opened (Fig. 21) and its depth is presented in normal cross-section. Corrosion attack (Fig. 22) due to improper water preparation contributed to fatigue crack initiation by variable loading.

The steam-turbine rotors are subjected to cracking by a variety of failure mechanisms, sometimes with catastrophic result by complete destruction, as was the case here. Therefore, special attention should be given to rotor and blade upgrading and repairing techniques.

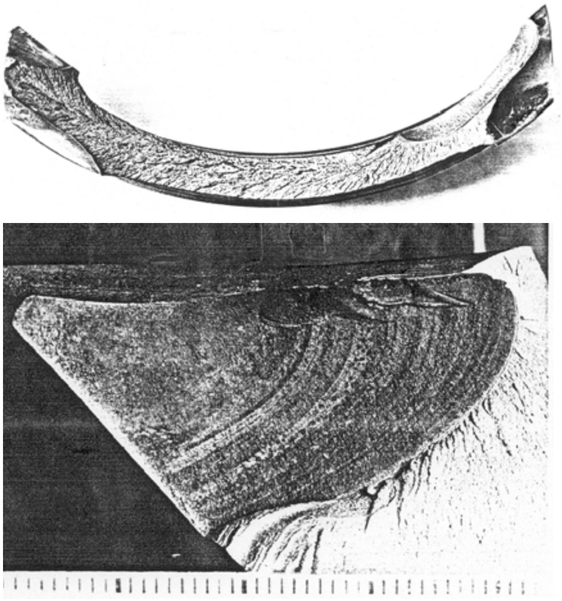

Figure 18. Blade fracture from fatigue crack in upper corner (top) with visible striations (bottom), /27/.
Slika 18. Lom lopatice je krenuo iz zamorne prsline na gornjoj ivici (gore), uz vidljive strije (dole), /27/

Figure 19. Second blade fracture started from a fatigue crack, /27/.
Slika 19. Lom druge lopatice je počeo iz zamorne prsline, /27/

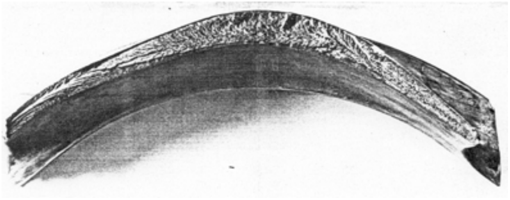

Figure 20. Brutal fracture of blade due to overloading, /27/.
Slika 20. Nasilni lom lopatice zbog preopterećenja, /27/

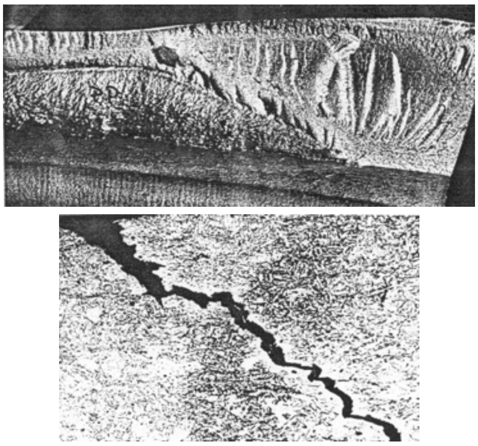

Figure 21. View of developed crack surface from Fig. 21 (top) and normal cross-section (bottom), /27/.
Slika 21. Izgled površine razvijene prsline sa sl. 21 (gore) i upravni poprečni presek (dole), /27/

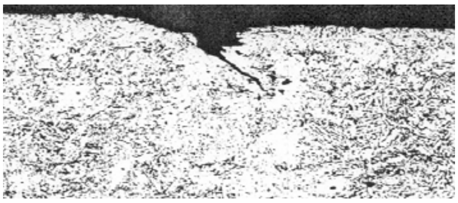

Figure 22. Corrosion attack at blade surface, /27/.
Figure 22. Korozijski zajed na površini lopatice, /27/

Special cases – civil engineering

Although civil engineering objects are constructed for long service time, as presented for ancient structures of stone, the new designed and constructed objects can be in risk to fail. This is the case with bridges, where several failures ended with catastrophic consequences (Fig. 7).

Very tall buildings also require special consideration regarding structural integrity and safe service, since their failure can be catastrophic. Developments in design, materials and technology today enable to construct exclusive buildings, up to the 828 m Burj Khalifa (Fig. 23) in Dubai, United Arab Emirates /28/, declared as being the "Tallest Building in the World" at its opening on 4 January 2010. It is taller than any other manmade structure ever built. The 280 000 m^2 reinforced concrete multi-use tower is predominantly for residential and office usage, also containing retail shops and a Giorgio Armani Hotel.

This is to remind that in such a large building, everyday life for a number of people has to be organised. Hence, it is necessary to assure many elevators, water supply, electricity, air conditioning, and so on. The usability and functionality of the whole building depends on reliable and safe exploitation, i.e. the integrity of individual subsystems.

Figure 23. Burj Khalifa (828 m), tallest building in the world, /28/
Slika 23. Burž Kalifa (828 m), najviša zgrada na svetu, /28/

Since such building height has never been attempted before, it is also necessary to ensure that all utilized technologies and methods are of sound development and practice. The designers sought to be able to use conventional systems, materials, and construction methods, modified and utilized in new capacities, to achieve such a lofty goal.

The task was to provide an efficient building in terms of its structural system and in its response to wind, while still maintaining the integrity of the initial design concept. The floor plan of the tower consists of a tri-axial, "Y" shaped plan, formed by having three separate wings connected to a central core, as designed by William Baker, /29/. As the Tower rises, one wing at each tier sets back in a spiralling pattern, further emphasizing its height. In addition to its aesthetic and functional advantages, the spiralling "Y" shaped plan was also utilized to shape the Burj Khalifa to reduce wind forces on the Tower, as well as to keep the structure simple and to foster constructability. The structural system can be described as a "buttressed" core, and consists of high performance reinforced concrete wall construction. The result is a tower that is extremely stiff laterally and torsionally. It is also a very efficient structure in that the gravity load resisting system has been utilized so as to maximize its use in resisting lateral loads. The top of the Tower consists of an approximately 230 m tall structural steel spire, and the entire Tower is founded on a 3700 mm thick reinforced concrete pile-supported raft foundation.

Here, as an illustration, one of the Seven Wonders of ancient World, the lighthouse of Alexandria, is present by the drawing made according to saved data (Fig. 24), since it was destroyed by several earthquakes. With evaluated height up to 140 m, it was the tallest building of the age, /30/. Compared to Burj Khalifa, being both most attractive in the time of construction, it is possible to conclude that the available knowledge based on theory and experience was used in design and construction. For that it is reasonable to declare Burj Khalifa as world wonder of our era.

Figure 24. Lighthouse of Alexandria drawing by Thiersch, /30/.
Slika 24. Aleksandrijski svetionik, crtež Tirša, /30/

Continuous developments in design and construction of more and more demanding objects made them to be prone to failure. Hence, the introduction of procedures to assess their integrity was required, and these days available in different approaches, /31/. It might be supposed that structural integrity was required also in ancient times: the laws of Hamourabi included punishment by death for the constructor of eventually failed buildings.

Special cases – mechanical engineering

The forces, to which parts and components of different machines are subjected to, can vary significantly, and can do so at an important rate. The forces which a boat or aircraft are subjected to, vary enormously and will do so thousands of times over the structure's lifetime. Many of them are of impact character. In addition they can be in many cases unpredictable. Structural design must ensure that structures are able to endure such loading for their entire design life without failing. Only recognising these circumstances it was possible, respecting all limitations involved by codes, standards and directives, to produce an advanced structure, using available materials, as for the largest passenger airliner Airbus A380, /32/, shown in Fig. 25.

Figure 25. Airbus A380, the world's largest passenger airliner.
Slika 25. Erbas A380, najveći putnički avion na svetu

Special cases – microprocessors, micro- and nano- structures

Unbelievable progress in nano materials and related sophisticated devices and structures, including microprocessors and other informatics and control equipment, expressed by hundreds of millions of units in everyday use and in science, can in general hardly be explained and described. Only some reflections about this topic will be indicated here in terms of the title and intention of this article, not entering in the substantial achievements and capacity of this segment of human life. The problem is so complex that the human mind can understand only some segments, but not the full meaning of development and exploitation of available knowledge and information technologies.

The design principle, applied in the construction of Burj Khalifa, allowing construction of such tall building based on the approach of its spiral character, might be imagined only after applying the same principle in the development of informatics devices and their application by scientists. This trend towards the moment when technological change will surpass the human mind is named "technological singularity", /64/. This short explanation can serve as an excuse why this topic is not considered in more detail.

The extended use has confirmed that reliability is a very important characteristic of microprocessors, micro- and nano- structures in service. In this case, reliability also includes the notion "structural integrity" in it. The reason is that structural integrity in an elementary meaning refers to structure, both in civil and in mechanical engineering, and to crack initiation and development in them. Sizes of micro- and nano- structures are extremely small compared to the size of a crack and the region ahead the crack tip through which the crack develops, /33, 34/. Hence, the "crack" as described in fracture mechanics is not applicable in the nano world, and the fracture process has to be considered and analysed in a different way. So, when applied here in connection with the nano world, the term "reliability" will include also structural integrity.

Significance of structural integrity assessment

Three classes of structures in term of structural integrity, reliability and safety can be recognised from presented cases of saved structural integrity and failures.

The first class includes structures that preserved their global integrity without special care even for centuries. In general, civil engineering objects produced of stone and other natural materials, and designed and constructed according to the inherent flow of forces in those materials are not prone to fail, even when experiencing local deterioration. This is to mention that their design and loading in use cannot induce crack opening (growth by mode I in fracture mechanics), required for crack extension. Typical examples are presented in Figs. 2, 4, 5 and 9. The significance of their structural integrity is in that they, in a more or less complete preserved form, can document the era in which they were constructed and as cultural monuments. Together with many others, they are declared as UNESCO World Heritage Sites, and in that sense they had been restored, if required.

The second class include a series of various machines, equipment, devices, accessories, which can fail due to different causes, and in different circumstances they do fail. Only some examples of failures are presented here, indicating the significance of structural integrity assessment. To get an impression on how this problem is important, objects for which structural integrity assessment should be performed are in short:

- Pressure equipment: pressure vessels, storage tanks and containers, pipelines, components of process plants, etc.
- Pressure equipment operating at elevated and high temperatures: boilers, steamlines, power plant components.
- Transport means: trains, cars, trucks, airplanes, ships, etc.
- Engines: steam engines and turbines, internal combustion engines, gas turbines, pumps, compressors, etc.
- Earth moving machines: excavators, grinders, dumpers, bulldozers, etc.
- Space equipment: rockets, shuttles, etc.

Mostly, these objects are designed for many components, devices, accessories, e.g. the motor car consists of a body, engine, transmission, electrical accessories, heating and cooling systems, wheels, brakes, but also an introduced microprocessor control system, requiring a high level of reliability in operation.

Used materials are metals (steel, cast iron, aluminium, titanium, brass, magnesium) and non-metallic materials (plastics, composites, glass).

Presented failure examples vindicate introduced strict requirements and special care for structural integrity that on the other hand were insufficient to avoid complete occurrence of failure. This is illustrated by bridges. The contemporary steel bridge I-35W failed after only 40 years service (Fig. 7). The Bridge on the Drina (Fig. 9) preserved structural integrity for centuries, thanks to proper maintenance and repair. However, at present it is saved as a historical monument; it is not ready for its initial purpose since traffic conditions have changed drastically from the time of its construction. The Iron Bridge (Fig. 8) is also interesting from a structural integrity point of view. After 160 years of service it was barred to vehicular traffic in 1934 and now is declared as an UNESCO World Heritage Site. Some of the present-day cracks in the cast iron might be casting cracks and did not develop during exploitation of the bridge.

Having in mind the role of fracture mechanics in structural integrity assessment, crack initiation and its development are basic approach in programs for structural integrity assessment. In that sense, the defect in a structure and stress concentration are basic points to be considered. Once initiated, the crack can develop by different mechanisms. Most important are brittle fracture, yielding (stable crack growth by increased static load), fatigue caused by variable loading (high and low cycle), creep, corrosion and stress corrosion. Some of them can have mutual effects. Examples of brittle fracture, stable crack growth, fatigue and corrosion are already presented. From a structural integrity point of view and probability to avoid failure cases of the bucket wheel excavator (Fig. 15) and turbine blades (Figs. 18–22) are of special interest, since the failure could be avoided by proper inspection and maintenance.

The Eiffel Tower (Fig. 10) is a typical example of how structural integrity can be preserved for a ling time by proper maintenance and repair.

The third class of structures are sophisticated complex systems, as the Burj Khalifa (Fig. 23). In such a system, elementary structural integrity is applicable only to subsystems and their components, and the use of the whole system has to be strictly controlled by computers.

APPLICABILITY OF STRUCTURAL INTEGRITY ASSESSMENT

The ability to apply procedures for structural integrity assessment is enhanced by continuous development in theoretical, numerical and experimental aspects, and through knowledge gained from case studies. The most important contribution, the consideration of crack behaviour in stressed components, as possible initiation of fracture, has been enabled by introduction of fracture mechanics (FM). Before FM, only smooth and idealised shapes had been considered in calculation, and the designer had to make a number of assumptions and correction factors, mainly gathered from experience, to adopt idealised shapes.

It is to say that structural integrity is an engineering category. Based on theoretical solution, the strength of the selected material has to be adopted in design by calculated size of loaded component, neglecting possible defects. In order to assure the safety of the structure, correction factors for engineering assumptions and simplification, covering possible uncertainties, are introduced. The same approach is applied also when cracks are considered, what has become possible only after the development of fracture mechanics.

Design of pressure vessels

This approach is presented in short as applied to design of pressure vessels, because it is also interesting for structural integrity assessment.

The design of pressure vessels is based on maximal hoop stress, σ, for a cylindrical vessel of diameter, D, and wall thickness, s, exposed to inner pressure, p, by using the formula, derived in the theory of elasticity,

$$\sigma = \frac{Dp}{2s} \le \sigma_{all} \qquad \sigma_{all} = \frac{R_p}{\nu} \tag{1}$$

The parts are dimensioned so that the applied stress, σ, is lower than allowable stress, σ_{all}, in order to assure safety in service. The value of σ_{all} is specified in a way that plastic deformation is not permitted, so the limiting stress is material yield stress, R_p, determined by standard tests, reduced by the safety factor $\nu>1$, specified in design codes.

Some comments are necessary here. The stress, which cannot be measured directly, but via elongation, is used for calculation, and this is the first adoption of the theory to practical application in design. The next simplification is that the material is considered homogenous, with uniform properties in all directions, what is far from reality.

A very important effect of the manufacturing process is not taken into account by Eq.(1). Most frequently, welding is applied for joining of vessel parts. Due to different microstructures of welded joint constituents (parent metal – PM, weld metal – WM, heat-affected-zone – HAZ) mechanical properties are different, and hence the behaviour of the welded joint under loading is non-uniform. In addition, the imperfection of the welded joint shape and inevitably induced defects produce important stress concentrations /1/.

In that sense, the theoretical approach has to be adopted for practical use by involving requirements and recommendations covered by codes, standards, and recently introduced European directives, as in the considered case – The Pressure Equipment Directive (97/23/EC), /35/.

Fracture mechanics parameters and their application

The definition of stress concentration in an elastic body around a circular hole in an infinite plate, given by Kirsch, mathematical analyses of stress distribution performed by Inglis /36/, Muskhelisvili, Westergard and Neuber, opened the opportunity to develop fracture mechanics. After extended theoretical and experimental investigation of stress distribution in loaded components, the possibility to involve crack parameters in stress analysis has opened, /37/.

The development of FM parameters should be considered from different aspects when applied to complex problems of structural failures, affected by many factors. These aspects concern gathered experience, extensive knowledge involved in theoretical background, experiments done on highly sophisticated equipment, computerised modelling and numerical analysis, and as probably most important, practical aspects. This allowed to develop standards and codes and use them in everyday practice in the design, manufacture, inspection and maintenance of structures and materials to prevent failures.

Two main contributions of FM in the development of engineering structures are connected with fracture itself (prevention and analysis) and development of new materials based on specification with defined FM parameters.

Three essential fracture mechanics parameters are: stress intensity factor, K, path independent J integral and crack opening displacement (COD), δ. Derived in linear-elastic fracture mechanics (LEFM), the stress intensity factor, K, describes crack behaviour under loading in the elastic range. As initial references can be taken that of Griffith, /38/, and Irwin and Kies, /39/. The most convenient parameter for elastic-plastic fracture mechanics (EPFM) is the J integral, defined by Rice, /40/. Crack opening displacement (COD), δ, defined by Wells is introduced as an empirical factor. These factors are interconnected by different relations.

Some retrospective of FM, as the development and application of involved parameters /41, 42/, can help to better understand applied structural integrity assessment.

In the analysis of fracture strength, Griffith /38/ recognised that it is possible to derive a thermodynamic criterion for fracture by considering the change of total energy of a cracked body with increased crack length. Only if the total energy should decrease, would the crack extend spontaneously under applied stress. Applying the energetic approach to the body as a whole, it is possible to neglect local stress concentration around the crack tip (Fig. 26) and after complicated calculus derive a useful expression for fracturing stress. New surfaces of the growing crack are created, and since stresses and displacements ahead of the infinitesimally extended and the initial crack tip are almost identical, the energy increase during crack extension is simply the unit “work to fracture,” 2γ, multiplied by the area of new produced crack surfaces. Griffith proposed that the driving force for crack extension is the difference between the energy released for crack extension and that needed to create new crack surfaces. The calculation applied by Griffith is complicated, but the same result is obtained by simplified calculation, /37/, used here to present an approach to modelling.

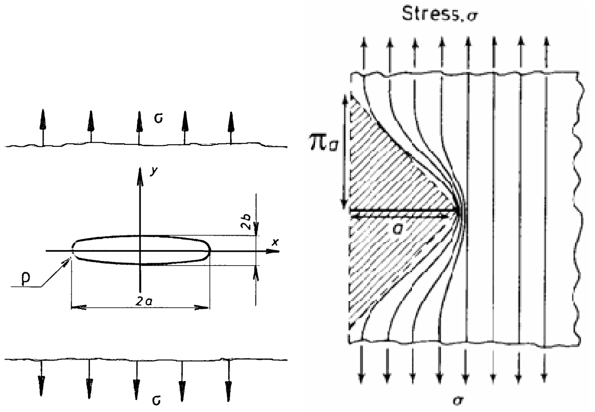

Figure 26. Griffith’s crack: geometrical configuration (left) and simplified presentation (right), /34/.
Slika 26. Grifitova prslina: geometrijski oblik (levo) i uprošćena skica (desno), /34/

Half-crack length, a, exposed to the applied stress σ (Fig. 26), and in extended state, $(a + da)$ is considered under fixed grip conditions. Stress-free regions above and below the crack can be roughly triangular in shape and extend to a height βa ($\beta = \pi$). Then, for length a, the strain energy release per unit thickness is given in plane stress by ½ × stress (σ) × strain (σ/E) × area (πa^2), i.e.

$$U = -\frac{1}{2}\sigma\frac{\sigma}{E}\pi a^2 \qquad (2)$$

For a length increase, da, the decrease of strain energy is

$$dU = -\frac{\sigma^2}{E}\pi a\,da \qquad (3)$$

For plane stress condition the change in energy is

$$\frac{\partial U}{\partial a}=-\frac{\sigma^2}{E}\pi a \tag{4a}$$

In plane strain, the tensile strain is given as $\sigma(1-v^2)/E$ (v is Poisson's ratio), and $\partial U/\partial a$ is:

$$\frac{\partial U}{\partial a}=-\frac{\sigma^2(1-v^2)}{E}\pi a \tag{4b}$$

Obtained results combine the energy U, remote applied stress σ, and involve the crack length, a, for the first time in calculation. It is not possible to directly analyze crack effect /37/, hence the crack is modelled in an ideal crystalline body by increased interatomic distance at the tip under applied remote stress σ (Fig. 27), considering the change in crack driving force F with crack extension at the atomic level.

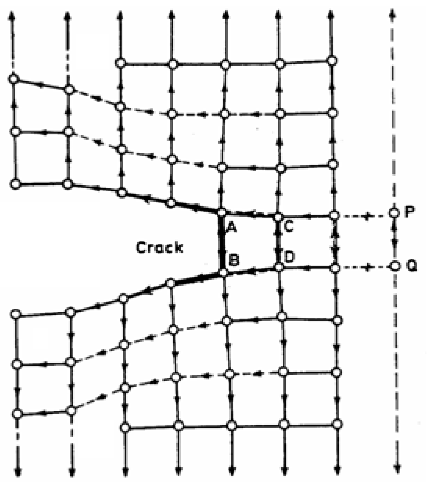

Figure 27. Development of a crack in an atomic model.
Slika 27. Razvoj prsline u atomskom modelu

This is possible only with assumptions (homogenous metallic material, uniform atomic structure and atomic force) and simplifications (stress σ is the sum of the forces, F, acting between successive pairs of atoms in the crack plane, fracture occurs across a particular crystallographic plane in the cubic lattice with initial atomic spacing b_0). At the same time, several limitations have been induced. Material strength, $\sigma_{\max}$, is taken as a tensile stress σ, that must be applied to cause crack extension, and further approximation is necessary, the value of F required to cause fracture corresponds to that needed to separate an isolated pair of atoms, such as A–B. For a pair of atoms, as A–B, C–D, ... P–Q it is possible to draw a curve representing their energy of interaction as a function of distance of separation b, Fig. 28.

The resultant energy, U, exhibits a minimum at the equilibrium lattice spacing b_0 (Fig. 28a). Some energy must be spent to increase the distance between atoms b, and the total energy, necessary to separate two atoms, is given by U_0. The derivative of obtained curve is the curve: force (dU/db) vs. displacement (b), with initial slope equal to the elasticity modulus, E, and total area under it equals twice the surface energy, 2γ, considering both sides of the extended crack.

Further approximations allow to derive the relationship, /37/,

$$\sigma_{\max}=\sqrt{\frac{E\gamma}{b_o}} \tag{5}$$

where $\sigma_{\max}$ is ideal strength of material, and approximate fracture stress, having in mind the value γ.

A fracture stress value the order of E/10 may be estimated from Eq.(5), using the value of γ the order of $0.01Eb_0$, applicable to many metals. Strengths of crystals and glasses in practice tend to be lower than this value by two orders of magnitude. Ideal fracture stress can be attained locally, but macroscopically, the homogeneous sample might contain small defects, causing discrepancy between predicted and actual values, as Griffith had suggested, /38/.

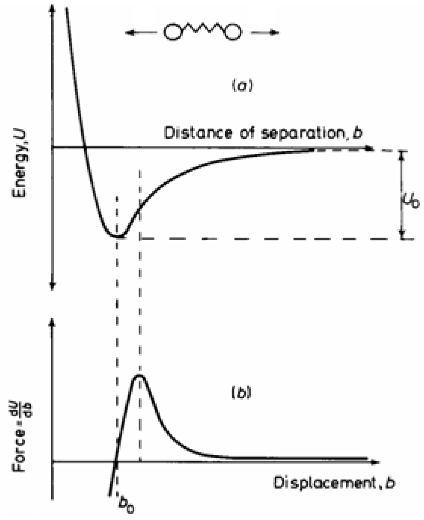

Figure 28. (a) Bonding energy as a function of atomic distance at separation, (b) Force–displacement curve.
Slika 28. (a) Energija privlačenja atoma u zavisnosti od rastojanja atoma pri razdvajanju, (b) Kriva sila–pomeranje

To understand the fracture stress, an elliptical defect is supposed in an infinite body (Fig. 26, left), with axes $2a$ and $2b$, lying normally to the applied stress, σ. The concentrated value of stress at the ellipse ends would be, /36/,

$$\sigma_{yy}=\sigma_{\max}=\sigma\left(1+\frac{2a}{b}\right)=\sigma\left[1+2\left(\frac{a}{\rho}\right)^{1/2}\right] \tag{6}$$

Here, $\rho = b^2/a$ is the radius at the tip of the ellipse. For a crack-like defect, ρ can be taken as the lattice spacing b_0. Then, since $2\sqrt{(a/b_0)} >> 1$ one would obtain:

$$\sigma_{yy}=\sigma_{\max}\cong 2\sqrt{\frac{a}{b_o}}\sigma \tag{7}$$

Comparing Eqs.(5) and (7), the stress at fracture, $\sigma_{\max}$, is:

$$\sigma_{\max}=\sqrt{\frac{E\gamma}{4a}} \tag{8}$$

It can be seen immediately that, for $\gamma = 0.01Eb_0$, as before, a defect length $2a$ of $5000b_0$, say 1 μm, is sufficient to lower the fracture strength by two orders of magnitude.

The Eq.(6) for stresses around an elliptical hole is derived on the basis of linear elasticity. Eq.(5) is based on a supposed sinusoidal atomic stress-strain curve. So, one has to have in mind that the macroscopic applied stress is correlated here to the atomic force–displacement laws, and this is the next assumption involved in the model.

Also, the decrease in potential energy is represented by values of $\partial U/\partial a$, released when a crack extends infinitesimally δa under constant load.

The Griffith criterion for fracturing a body with crack of half length a may be visualised, as in Fig. 29a, by drawing the energy change with crack length. In plane stress, for example, the total energy, W, consists of potential energy, U, and surface energy, S, i.e.:

$$W = U + S = -\frac{1}{2}\frac{\sigma^2 \pi a^2}{E} + 2\gamma a \qquad (9)$$

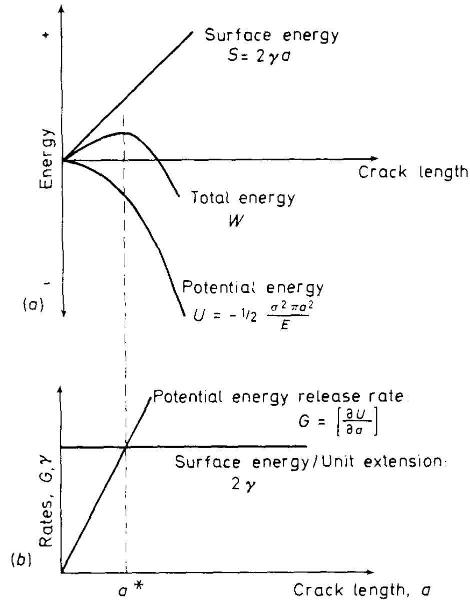

Figure 29. (a) Variation of energy with crack length. (b) Variation of energy release rates with crack length. (a^* is the critical value).
Slika 29. (a) Promena energije sa dužinom prsline. (b) Promena brzine oslobađanja energije sa dužinom prsline (a^* - kritična vrednost)

The maximum in the total energy curve for $\partial W/\partial a = 0$, produces

$$\frac{\sigma^2 \pi a}{E} = 2\gamma \qquad (10)$$

This is depicted in Fig. 29b by the intersection of the line $-(\partial U/\partial a) = \sigma^2 \pi a/E$ with that of 2γ. The positive slope, $(\partial U/\partial a)$, defined as potential energy release rate for crack extension under constant load for unit thickness, is the crack driving force, G. Comparing with Eq.(4), the Griffith fracture stress for a given crack length becomes:

$$\sigma_F = \sqrt{\frac{2E\gamma}{\pi a}} \text{ in plane stress} \qquad (11a)$$

$$\sigma_F = \sqrt{\frac{2E\gamma}{\pi(1-\nu^2)a}} \text{ in plane strain} \qquad (11b)$$

These expressions are similar in form to those derived for the crack tip using the Inglis /36/ solution for stress concentration. Griffith's approach considers only the initial and final states and is not concerned with the details of fracturing over the length δa; so it represents only a necessary condition for fracture, which may or may not be sufficient. The Griffith approach could show that total energy of the system would decrease, yet the hole would not extend without sufficient stress concentration at blunted elliptical ends to attain the local fracture stress, that is plane strain condition.

The most important aspect for fracture mechanics is that the crack size, a, is related to applied remote stress, σ, and material property, in the form of surface energy, γ.

These results allowed to be expressed by basic parameter of fracture mechanics, stress intensity factor, K, in the form already mathematically defined

$$K = Y\sigma\sqrt{\pi a} \qquad (12)$$

where Y is a factor of geometrical shape and final sizes of the considered component. The critical value, K_{Ic}, is a material characteristic and can be determined experimentally using standards for plane strain fracture toughness. It is to mention that the plane strain condition must be fulfilled in K_{Ic} testing, thus two requirements are prescribed in standards. The first is a very sharp crack tip (such as a fatigue crack) and the second is sufficient thickness of specimen, which can prevent plane stress condition and shear lips. The required thickness for brittle material is small, but for the ductile material could be of size which cannot be tested on available equipment. If the thickness is not sufficient, obtained results present critical value of fracture toughness, K_c, for considered thickness, but it is not a material property.

A structure is reliable if the applied stress intensity factor K is less than the plane strain fracture toughness of the material, K_{Ic}:

$$K \le K_{Ic} \qquad (13)$$

Linear elastic fracture mechanics (LEFM) can be applied to problems in which the plastic zone is small compared to crack length. Fracture is then characterised by plane strain fracture toughness, K_{Ic}, and the decisive value for brittle fracture is surface energy, γ. When plane stress dominates, the plastic zone is larger; but if failure occurs at net section, at stress levels much lower than yield stress, problems may be tractable by LEFM based methods.

Experience gained in the project "Fracture mechanics of weldments", /43/, suggests to apply J integral as a fracture mechanics parameter, due to offered advantages:

- there is solid theoretical background for the J integral, for both brittle and ductile crack behaviour;
- specimen size for obtaining valid results is significantly lower compared to specimen for stress intensity factor;
- it is possible to use critical J integral at crack initiation, J_{in}, a measure of fracture toughness, J_{Ic}, instead of plane strain fracture toughness, K_{Ic}, as a material property;
- it is possible to express stable crack growth resistance in the form of J-R curve and apply it for structural integrity assessment, comparing it with numerically determined CDF curves, and applying a convenient model;
- developed J integral direct measurement method (Read) is very efficient in the experimental analysis of cracked component behaviour;
- properties of heterogeneous materials in different regions of heat-affected-zone (HAZ) can be analysed numerically using the J integral path independence.

It might be a great mistake not to mention an impressive achievement in fracture mechanics development, obtained by theoretical disciplines as mathematics, mechanics, theory of elasticity, theory of plasticity, strength of materials, establishing solid background for definition of stress intensity factor by mathematical expressions. Anyhow, *spiritus movens* was the failure of structures, sometimes catastrophic (Fig. 1), and lessons obtained from practice and experience, together with the need to obtain an applicable solution for the considered case. The basic equation of fracture mechanics in general form reads

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta) + \text{finite members};\ i,j = 1,2,3 \qquad (14)$$

and the form for practical use in structural integrity assessment is that given in Eq.(12).

Extended application of fracture mechanics parameters

In the fracture mechanics-based approach, the material should withstand maximal applied load when a crack-like flaw exists, see Eq.(12). This approach is shown in Fig. 30.

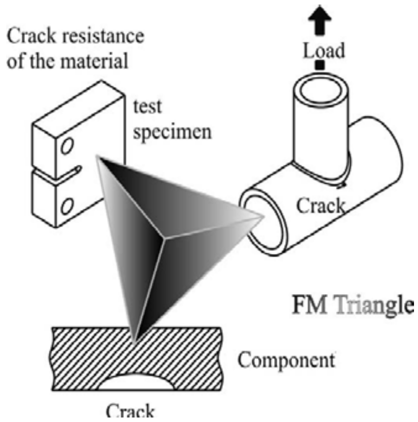

Figure 30. Fracture mechanics application in design.
Slika 30. Primena mehanike loma u projektovanju

Once established, and supported by mathematical background, basic parameter of LEFM, stress intensity factor, K, and Rice's J integral have also been applied in other conditions. Well known Paris law, based on stress intensity factor range, ΔK, although empirical in its nature, is a powerful tool for solving problems in fatigue. Looking for solutions of problems with a crack in a creep condition, C^* and C_t integrals are derived, based on J integral. The crack problem in a stress corrosion environment is also considered by applying the stress intensity factor, K_{Iscc}.

It is to emphasize that performed extensions are possible only after an introduction of a series of assumptions, simplifications and approximations, necessary to cover uncertainties and shortage in knowledge and experience in operation.

Searching for limits in fracture mechanics extension takes into account that mathematics is a fundamental science, inevitably applied to develop fracture mechanics and so the crack problem, the basis of structural integrity assessment. Limits in mathematics and science in general can be expressed by two mathematical symbols: → ∞ and → 0. Their meaning is clear in given form as approaching, but '∞' and '0' can be understood only when numbers are applied, as the tendency symbolized by '>' and '<'. The example of increasing size might be the Burj Khalifa and comparison to other buildings, with the comment regarding the reason of practical use of so tall buildings. On the other side, application of FM to nano level needs to consider the situation ahead of the crack tip.

Another simple conclusion is that science has no limits, also approaching zero, as confirmed by the development of nanomaterials and nanostructures, /33/. This might be significant for analysis of fracture as a process of material separation. Although fracture mechanics for macro, mezzo and micro scales are sufficient for structural integrity assessment of real and here considered objects, the scientists, following the infinite nature of science, are going much deeper. This is of importance for nano structures. Fast development of computers and software enabled simulation of processes and modelling of structures for detailed analysis.

Phenomena related to crack tip and its propagation are given in Fig. 31 as a classic picture of the steel structure, /34/. Most important is the fact that basic fracture mechanics formulae are developed for the continuum and homogenous material, and the consideration at the atomic force just help to confirm the applicability of obtained results, Eqs.(12) and (13). The size of edge dislocations is about 10^{-6} cm, subgrain slip band is sized to 10^{-4} cm, while large plastic strains extend to about 10^{-2} cm. The crack tip is connected with every illustration in Fig. 31, meaning it can be attributed to all presented levels, but with different approaches.

For better understanding the situation at the crack tip, new achievements are included in the actual scheme of the modelling procedure (Fig. 32). The complexity of this problem is recognised /44/, indicating the need for modelling and simulation as an inevitable step in modern approaches.

The range in which continuum mechanics theories are applied is very narrow. All material properties differ when they are averaged over different regions within each grain that can be traced to crystal lattices. When load is applied, the morphology of present defects and imperfections can be changed, complicating the analyses. At reduced scale size the changes may occur continuously, such that equilibrium cannot be reached and the process is in non-equilibrium. When the use of an ordinary continuum mechanics theory that assumes equilibrium and material homogeneity fails, one preferable assumption is not applicable. This situation needs modelling and simulation, since experiments and calculations are not possible yet at this level.

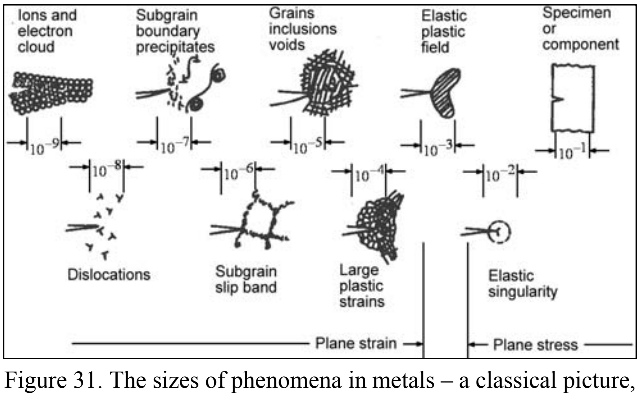

Figure 31. The sizes of phenomena in metals – a classical picture, presented in centimetres, /34/.
Slika 31. Veličine pojava u metalu – klasična slika, prikazana u centimetrima, /34/

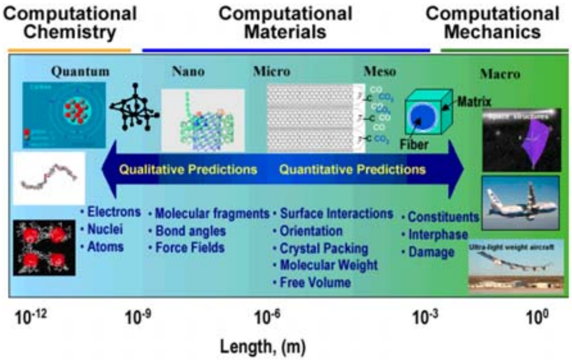

Figure 32. Length and time scales in material modelling, /44/.
Slika 32. Razmere dužine i vremena u modeliranju materijala, /44/

Data required for structural integrity assessment

According to Fig. 30, three sets of data are necessary for structural integrity assessment:

1. Data about applied stress level
2. Values of material characteristics – FM parameters
3. Crack location and size

These data can be introduced in the analysis with different degree of accuracy in accordance with required assessment certitude. They can be predicted or evaluated for a rough analysis. More explicit final results can be obtained with accurate measurement of required data values on the considered object, e.g. using strain gauges for stress determination, /45/, and laboratory testing of FM parameter according to standards, /46/. Very accurate values of stress and its distribution are also obtained by modelling, /47, 48/.

However, it is a very complex task to determine the data on crack location and size. There are a series of applicable non-destructive testing (NDT) methods, see e.g. /49/, but the consideration of these methods is beyond the topics considered in this paper.

PROGRAMS FOR STRUCTURAL INTEGRITY ASSESSMENT

More detailed structural integrity assessment is enabled after a developed theoretical background. It is recognised that the crack, the most dangerous defect in a structure, can be an initiation of fracture and for the integrity assessment of cracked component, the formulation and determination of crack parameters is a pre-requisite. Anyhow, significant efforts had been involved to describe the crack behaviour in a loaded structure.

Several programs for structural integrity assessment are developed and practically accepted. Probably more extended is the European procedure SINTAP (Structural INTegrity Assessment Procedure for European Industry), /50/. The project SINTAP included the experience of practical directives for use, explained in PD 6493:1991 (replaced by BS 7910:2005: Guide on methods for assessing the acceptability of flaws in metallic structures), as a simplified treatment of use of fracture mechanics methods to establish acceptance levels based on fitness for purpose, on fracture mechanics analyses and experience with cracks in welded structure. It offers varying levels of complexity in order to allow maximum flexibility gained from the application of existing procedures and has comprised activities such as collation of published information, assessment of material behaviour, optimisation of industrial procedures and the derivation of methods for treating assessment methodologies, all with specified limits for application.

Structural integrity assessment is of special importance in component operation when decisions depend on whether a damaged component should be used, and if so, under which conditions. The decision for further use is reached as based on state evaluation and the adopted term is “Fitness-For-Purpose” (FFP). Two effects are significant in FFP assessments. The first is the choice of an applicable procedure for defect awareness and integrity assessment of a damaged structure. The other is in determining defect type, its size and location within the structure. Accuracy of fitness assessment depends on the exactness of defect data. This is why methods for detecting defects and their characterization are intensively developed with the idea of efficient tracking of detected flaws in service.

Stress and strain analyses stipulates knowledge of loading and its accurately defined characteristics and operating conditions, also taking into account impacts of the operating environment. Having in mind the problem nature, development of probability methods, their excellent knowledge and conditions of use are relevant for efficient FFP assessments. All of these details are a prerequisite for the use of developed procedures for determining the significance of damage. This relates to corrosion damage assessment procedures, material fatigue, fracture appearance and development, and to high temperature influence and creep. A considerable part of these procedures is included in SINTAP at a practical level.

A request for data on defects needs to be added to all of this that should be accurate with a description of characteristics, sizes and defect locations.

Just to mention some other programs: R5; R6; API 579; API 1104. The selection of an appropriate procedure depends on the mode of failure (fracture, fatigue, creep or corrosion), type of component, service temperature and user’s experience. Some of the above procedures are specific to a certain industry, such as R54 or R65, developed for the nuclear industry, whereas others such as BS 7910 have more general applications. Most interesting programs are for mechanical and civil engineering, related to the built environment (as bridges, foundations, offshore structures, pipelines, power stations, process plants, boilers and pressure vessels, water and wastewater infrastructure) and the variety of mechanical (moveable) structures (airframes and fuselages, coachworks and carriages, cranes, elevators, excavators, marine vessels, and hulls). The design of static structures assumes they always have the same geometry (in fact, so-called static structures can move significantly, and structural engineering design must take this into account), but the design of moveable or moving structures must account for fatigue, variation in the method in which the load is resisted and significant deflections in structures.

A further problem is connected to crack detection, location and sizing in a structure. Development of different non-destructive testing methods with different levels of applicability and sensitivity enables an accurate definition of the crack, contributing significantly to the quality of structures and the high level of structural integrity, /49/.

However, many limitations have been posed when cracks are considered. The procedure for determining the critical crack size is illustrated in Fig. 33, /50/.

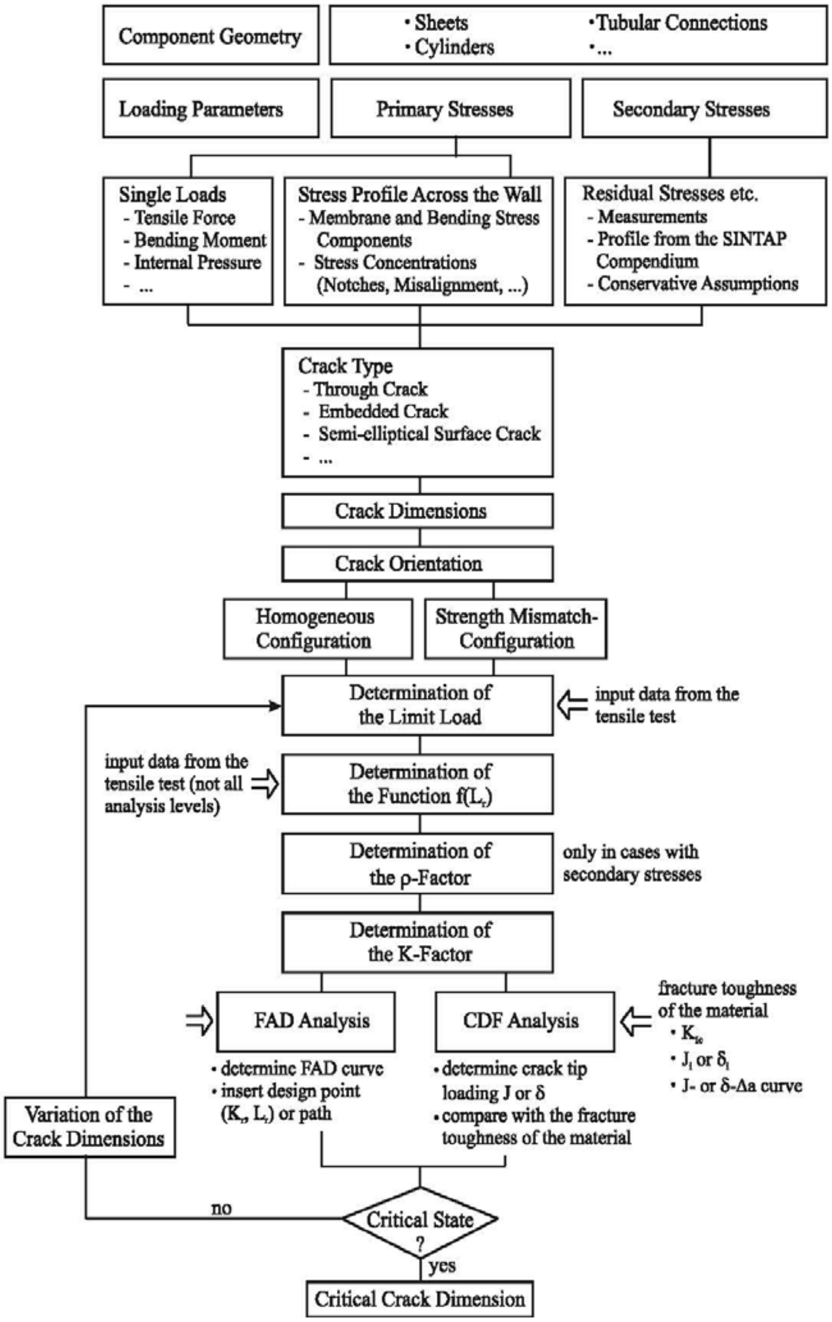

Figure 33. Flow chart for the determination of critical crack size using European SINTAP /50/
Slika 33. Tok određivanja kritične veličine prsline prema evropskom programu SINTAP, /50/

Some basic items of SINTAP application will be addressed following this flow chart. In order to determine a critical crack size, the following input data are required:
- geometry and dimensions of the component,
- applied load, including secondary load components, such as residual stresses,
- information on crack type and orientation, and
- stress-strain curve and fracture toughness of the material.

A structure designed obeying codes, manufactured and inspected according to valid directives and operating and maintained in service following instructions, can be considered as healthy and without a jeopardized integrity.

On the other hand, many structures can operate with detected damage, but still their integrity is saved and they can be used for a certain time period. This can be the case with welded structures. The aim of structural integrity assessment of a cracked structure is to predict how the crack will behave, in order to make a decision on further service.

To do this, the following steps are necessary:
1. Non-destructive testing; to detect a defect, especially crack, to locate it and determine the size.

2. Stress-strain analysis. Applying sophisticated software it is possible to find out the stress state in the critical region. Based on this, crack-driving-force (CDF) can be defined.
3. Defining material resistance to crack. Fracture mechanics parameters, determined in properly performed tests, can describe the fracture toughness of the material.
4. Comparing CDF and material crack resistance one can assess the structural integrity.

This simple approach, accepted by analogy with calculation of component dimensions comparing applied stress and material strength, Eq.(1), is not simple when applied.

In order to evaluate the significance of defect (crack) it is necessary to model and calculate a crack-free and cracked structure, determine performance diagnostics in both cases, to model and calculate a cracked element in linear and non-linear range for various defect locations and sizes, including diagnostics of cracked structural element performance, /51/.

Diagnostics of cracked (defective) structure performance should respond on how crack location and size *a* (length or depth) affects the extent and distribution of deformation (maximal strain, crack opening displacement and its maximum), compliance value, magnitude and distribution of stress components, strain energy value and its change, strain energy at the element crack tip, and product of yield stress and crack tip opening displacement.

Recent trends for extended application

Increased computer and software development enables design of new control devices, continuous improvement and extended application of structural integrity assessment. Here, some selected examples will illustrate the importance of these trends.

Continuous monitoring

Improved and new developed devices are included in non-destructive tests for structural integrity assessment as an integral part, /49/. However, more attention is paid to the development of systems for specific purposes, consisting of modern devices and instruments, and connected with computers and corresponding software. Stereometric displacement measurement (Fig. 34) is of special interest for materials of heterogeneous structure, applied at locations of stress concentration, to monitor material behaviour when elasticity is exceeded and the plastic zone locally develops, /52/. Data obtained by this measurement are the basis for calculating fracture mechanics parameters, e.g. J integral, required for integrity assessment. Experience in continuous deformation monitoring, gathered in laboratory tests and experiments can be applied for monitoring structures in service. The problem is generally more complex and requires re-establishing a system proposed in the MOSTIS-EUREKA! Project (2006).

Ten years ago, about 187 000 bridges are classified as deficient in USA. The Federal Highway Administration (FHWA) has introduced a mandatory bridge management system and 10 000 bridges had been constructed or retrofitted per year. Non-destructive tests (NDT) by digital devices and non-destructive evaluation (NDE) by applying the modern database with test results are involved, /53/.

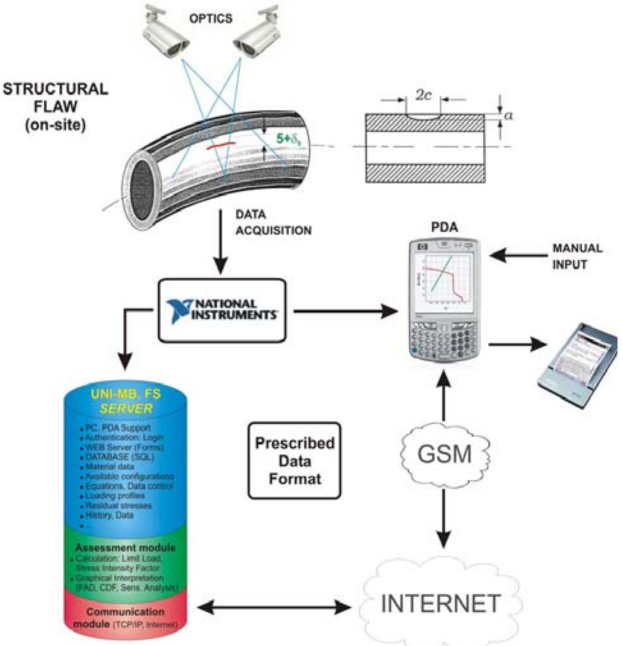

Figure 34. System for continuous monitoring of strain and damage on structure, data acquisition and fitness-for-service evaluation, /52/
Slika 34. Sistem za kontinualno praćenje deformacija i oštećenja, sakupljanje podataka i ocenu podobnosti za upotrebu

This fraction of steel bridges is important. According to FHWA data, in USA it is above 50%. The choice of NDT and non-destructive evaluation (NDE) methods depends on bridge type and materials used. Quantitative NDE and NDT data on bridge condition are necessary and can be wirelessly transmitted to an Independent Film Channel (IFC) server (Fig. 35).

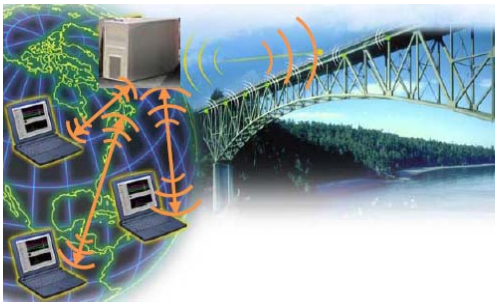

Figure 35. System for continuous monitoring of bridges, /53/.
Slika 35. Sistem za kontinualno praćenje stanja mostova, /53/

This is important for some types of hidden damages, e.g. corrosion of concrete reinforcement or fatigue cracks in steel bridges. Experience shows that the following methods are suitable and should be developed:
– Infrared thermography for quantitative inspection of bridge decks, detection of delamination in concrete.
– Radar system for bridge deck inspection with impulse radar and image processing to show the interior of reinforced-concrete deck (voids and reinforcements).
– Global bridge measurement using a portable laser-scanning system that quickly measures deflection of a bridge with an accuracy of 1 mm, also the vibration of bridge to determine bridge structural properties and to detect damage.

- Acoustic emission monitoring of fatigue crack growth in real traffic condition on highway bridge.
- Fatigue crack detection in steel, over lacquer protective layer, combining ultrasonic and magnetic test methods.
- Measurement of loads caused by heavy trucks and earthquakes, using steel sensors.
- Permanent recording of maximal strain of large bridges, by sensor based on the change of steel magnetic properties.
- Ultrasonic detection of voids and cracks using pulse-echo technique, C-scan and diffraction technique.
- Cable-stay force measurement, using laser vibrometer.
- Strain measurement using optical cable, applying interferometric method and Bragg grating.

Similar methods can be applied also in other situations and the list of applicable methods is wider. Proposed methods need further development and service experience.

Application of information technology standards in structural integrity of buildings

Important aspects of modelling are already introduced in standards, /53, 54, 55/. Precise determination of causes for potential failure and the assessment of structural life in civil engineering requires documented history with detailed building data. The needed documentation is diverse and consists of many paper or electronic documents included in the history during phases of conceiving, design, construction, exploitation, maintenance and restoration. Building records and surveys showed that almost 80% of failures that critically affect the lifecycle come from misconceptions in conceiving and design. The remainder results from errors in production and maintenance.

Object oriented modelling enables rapid and reliable development of complex systems for Building Information Model (BIM), (Fig. 36). It is standard in the software industry, for modelling all pursuits of information technologies in all branches of human life, /54, 55/. The basis of the electronic building model development interoperability are data models as the extensible markup language (XML) and Industry Foundation Classes (IFC), Fig. 37. Similarly, the IFC Bridge model is intended to manage the entire lifecycle of the bridge construction, /53/.

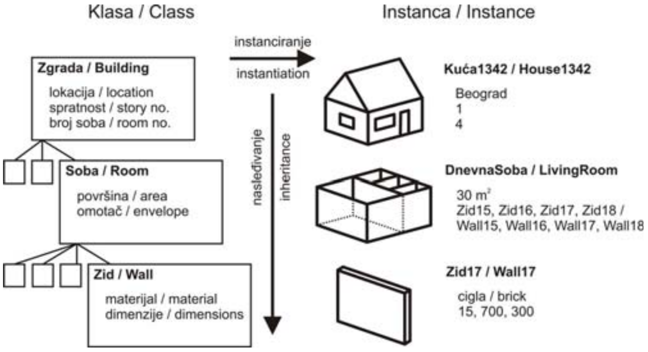

Figure 36. Object oriented modelling concepts for the Building Information Model (BIM), /54/.
Slika 36. Koncept objektno orijentisanog modelovanja za informatički model zgrade (BIM), /54/

BIM improves building planning, design, construction, operation, and maintenance by enabling all participants in the process to exchange and share building information using a same standardized data model. The benefits are:

– reduced loss of information during data ownership takeover from the various disciplines involved in the process;
– reduced errors because data are entered only once, afterward used and modified by all participants in the process;
– early conflict detection among building elements or functions which reduces all costs.

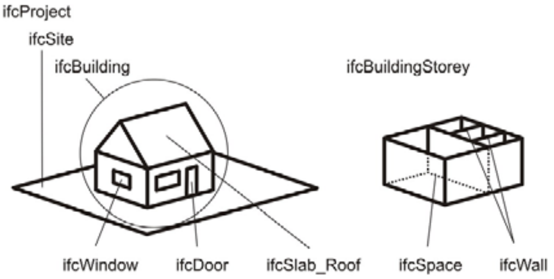

Figure 37. Example of Industry Foundation Classes (IFC).
Slika 37. Primer industrijskih baznih klasa (IFC)

In the analysis of remaining structural life, FEM software is a basic tool, so the IFC model has to be linked to it automatically. This option is accomplished by an interface to all significant applications integrated in the model.

It is impossible to imagine the design and construction of a system as the Burj Khalifa without object oriented modelling and information technologies. Very important parts of structural integrity, functionality and reliability, of this complex system depend strongly on structural integrity of subsystems, as lifts, supply water and electricity, air conditioning and many others, included in the object. Structural integrity of each subsystem should be assessed separately. On the other hand it is necessary, in addition to safety and security, to include functionality and reliability as components of integral structural integrity. In that sense, some redefinition of structural integrity needs to be considered.

Modelling and simulation

In about 40 years of development in material analysis at different size scales, the model presented in Fig. 27 could be substantially change involving new achievements. To illustrate this, the complex model obtained by hierarchical simulation approach is shown in Fig. 38, /33/. It integrates information obtained from more detailed smaller-scale – into coarse-patterned larger-scale models. This approach is proved successful when the physics at different scales are weakly coupled. It is feasible when, towards larger-scales, the information is passed via one or few common parameters, as inter-atomic potentials on molecular dynamics/ quantum mechanics (MD/QM) interface, virtually decoupled from smaller-scale models. This is the basis of so-called *ab-initio* method, which enabled to develop convenient algorithms, applicable to heterogeneous engineering material microstructures with various patterns by multi-field decomposition for describing material deformation and, ultimately, fracture. The potential energy of the system is formulated in terms of micro and macro stress tensors which account on deformation gradients, body forces and couples. On the boundary, the forces and moments are specified together with the geometry and the volume of the simulation domain. In this way *ab initio* method underlying QM approximations (based on tight-binding approach) is coupled with MD and, then, the MD model is coupled to macro scale with continuum FE models. In this approach FE mesh size is down-scaled to interatomic range. So, a very simple approach, applied in Fig. 27, is in Fig. 38 replaced by a very complex one.

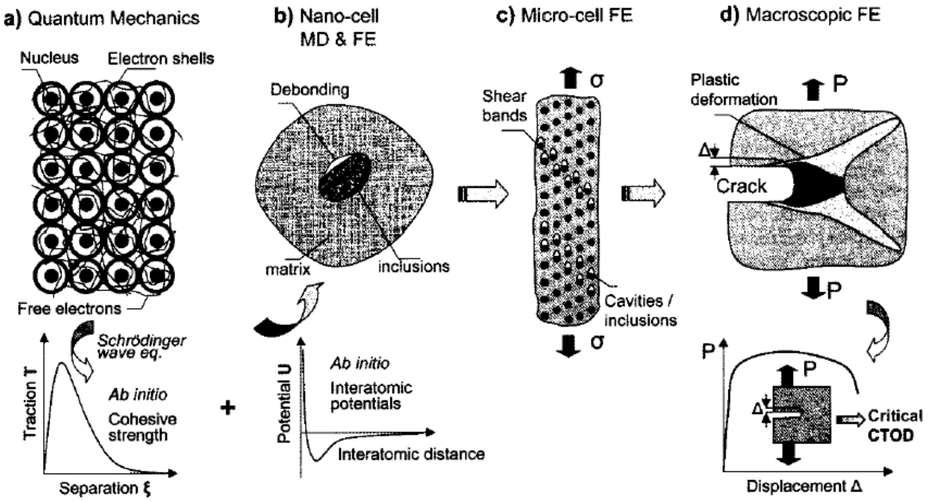

Figure 38. Hierarchical modelling: (a) quantum mechanics simulation; (b) molecular dynamics and finite elements models; (c) macro-cell and nano-cell; (d) macroscopic finite elements model for critical crack opening displacement assessment, /42/. MD–Molecular dynamic, FE–Finite element, CTOD–Crack tip opening displacement.

Slika 38. Hijerarhijsko modelovanje: (a) simulacija kvantne mehanike; (b) modeli molekularne dinamike i konačnih elementa; (c) makro-ćelije i nano-ćelije; (d) model makroskopskih konačnih elemenata za određivanje kritičnog otvaranja prsline. MD–Molekularna dinamika, FE–Konačni elementi, CTOD–Otvaranje vrha prsline

In Fig. 38, modelling of deformation and fracture behaviour for material design purpose concerns the development of the Cybersteel for naval applications. The steel is conceived to contain particles at two different scale lengths. Primary inclusions, order of mean size 1 μm, and nano-secondary particles, order of 0.1 μm, are considered. The former enhance the yield point and tensile strength, the latter improve ductility, also fracture toughness.

For a proper description of localised gradients of deformation, higher-order terms are included into constitutive equations. In hierarchical modelling, the simulation is performed independently at every size-scale level by solving the scale-specific constitutive equation. The bridging between levels is achieved by embedding the information gained by fine-scale simulation into the model of a superior size-scale level.

Hierarchical in combination with concurrent simulation is adequate here since the failure occurs at several well defined size-scales. Failure initiated by particle-matrix debonding at quantum scale, void nucleation and growth is typical at the mezzo-scale, shear deformation localisation appears within shear bands at micro-scale and, finally, material separation by fracture occurs at macroscopic level. It is to mention that significant simplifications are necessary here, which need to be proved as conservative by experiments.

At quantum scale, the failure mechanism is initiated by bonds breaking at inclusions-matrix interface. The cohesive strength, in terms of atom separation, as function of traction force, governs atomic debonding. The interface binding energy derived from this solution is regarded as key design parameter of Cybersteel (Fig. 38a). At nano-scale, the debonding of inclusion-matrix interface is simulated by a concurrent method. Matrix and particle regions are modelled by finite elements and the interface by molecular dynamics. Debonding on the interface triggers void nucleation. Further, the dynamics of void development, dependent on void volume fraction and distribution of nano-secondary particles, enables to simulate the constitutive law of deformation and plastic flow rule in a nano-cell (Fig. 38b).

At micro-scale (Fig. 38c), constitutive equations of deformation and the plastic flow rule are simulated concurrently, similarly as in nano-scale cells, having incorporated the constitutive equations and plastic flow rule inherited and passed from nano-scale simulation. The deformation behaviour of the matrix, according to its constituency at micro-level, as well as of primary inclusions (of micro-size, by difference to secondary particles of nano-size) is simulated as a continuum by FE. The debonding on matrix/primary inclusions is simulated by MD with a cohesive rule inherited from the simulation at QM level (Fig. 38a). Subsequently, the growth and eventually the coalescence of voids, under increased loading, are captured by FE simulation of the matrix. The observed shear bands, as prelude to final fracture, are simulated at this level. Under increased applied loading, continuum FE models of elastic-plastic fracture mechanics are applied (Fig. 38d). After significant prior plastic deformation at macroscopic level, fracture appears as a result of unstable plastic deformation, localised into a critical cross-section that is normal to the maximum of the applied principal tensile stress. Significant capacity of macroscopic plastic deformation under monotonously increased loading, owing to optimised size and nature of primary and secondary particles, coupled with high values of crack tip opening displacement demonstrated by simulation confer, from the design stage, high toughness to Cybersteel, which is confirmed in laboratory testing.

It should be remarked that the simulation of dislocation mechanisms, involved at the mezzo- level, is circumvented owing to the lack of clarified physical dislocation models, both as individual entities (e.g. electron configuration of dislocation core) and as dynamic ensembles. Details of physical processes at mezzo scale are implicitly covered, globally, in lower scale-size models at QM and MD levels.

The presented approach can be considered as a further and a very detailed extension of previously developed crack significance assessment, involving high level of theoretical based knowledge, gathered at different scales, but in fact it does not treat the situation at the crack tip. It demonstrates high level of applied theoretical background, capacity of modelling and numerical analysis and obtained practical effects, proved experimentally. It is to notice, the assumptions involved at different scales, generally intending to be conservative enough to assure requested safety and reliability, and thus integrity.

In this context one has to have in mind that within the plastic zone, there is (usually) a much smaller finite region of the process zone and its material properties bear no relation to those of bulk material. It is shown, /56/, that the maximal opening tensile stress is not at the crack tip, but at a small distance beyond, within the plastic zone, due to crack tip blunting and the decreased hydrostatic component of stress at the free surface: so crack propagation may be discontinuous and may take place in finite growth steps.

The applied approach in the performed modelling is in its nature an engineering one, since it involves several assumptions, which need to be verified, but the final results, development of material of specified properties has been proved in the laboratory. A very interesting aspect here is that nano level is induced in consideration of the fracture problem, indicating the possibility to extend the fracture mechanics approach to nanomaterials and nanostructures.

Application to nano level

The introduction of nano structures can be considered as an important extension in the area of engineering structures, and benefits of this extension are well recognized. Since the requirements regarding security, safety and reliability are very important for nanostructures, the attempt to apply FM parameters is natural, /33, 34/.

Since the size of nanostructures becomes comparable to the size of the cohesive zone, near a crack tip, new approaches for the prediction of crack propagation are offered. A new model is proposed by N. Pugno et al. /57/, as a modification of the Griffith theory. If the load exceeds a critical value at which a crack of given length is stable, the energy-release rate per unit area of crack advance, G, becomes larger than the intrinsic crack resistance, G_c, and as a consequence the crack propagates. In a perfect homogeneous solid in vacuum, the crack resistance energy per unit surface is identified with the cleavage surface energy, γ. Crack resistance is defined as $G_c = 2\gamma_c$. Within LEFM it is assumed that $\gamma_c = \gamma$. Quantized fracture mechanics (QFM), that modifies continuum-based fracture mechanics substituting the differential in Griffith criterion with finite difference, is formulated in /58/. This simple assumption has remarkable implications: fracture of tiny systems with a given geometry and loading conditions occurs at quantized stresses that are well predicted by QFM. The QFM theory introduces a quantization of the Griffith criterion to account for discrete crack propagation and discontinuous nature of matter at the atomic scale, and thus in the continuum hypothesis, differentials are substituted with finite differences.

Simulations with nanocracks of length $2c_0 < 2a < 50c_0$, where $c_0 = 0.2644$ nm for silicon carbide matrix shown in Fig. 39, were performed using the Tersoff potential for calculation of inter-atomic forces, /58/. Obtained results differ by 25% from the Griffith theory.

Modern atomistic methods and continuum methods for nanoscale modelling and simulation provide many insights on the behaviour of cracks at the nano-scale, /33/.

Continuum methods often start with extending the range of applicability of proven engineering methodologies to nano-scale phenomena. Recently developed Virtual-Internal-Bond (VIB) method is aimed in investigating fracture of such nanomaterials. It is demonstrated that, at a critical length scale typically of the order of nanometer, the fracture mechanism changes from classical Griffith fracture to a homogeneous failure near the theoretical strength of solids.

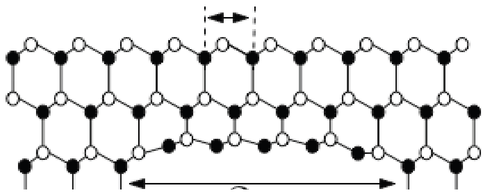

Figure 39. Geometry of the Griffith problem in the atomic-scale. Open dots represent carbon (silicon) atoms; the bond network is represented by lines.

Slika 39. Geometrija Grifitovog problema na atomskom nivou. Otvoreni krugovi predstavljaju ugljenične (silicijumove) atome; mreža veza je predstavljena linijama.

Crack size and tip region are very small when considered in a sample of macro- up to micro- scale, Fig. 32. This allows to consider the material as a continuous solid and apply stresses, strains and crack analysis as defined in mathematical and numerical models, in spite of the series of accepted simplifications. It is also possible to assume that the crack tip exists as a singular point in a continuum solid, producing here described consequences of loaded material behaviour. It is not easy to imagine crack tip as a point in Fig. 26, but also in Fig. 32, at a magnification higher than micro level. Hence, the validity of applied formulae at macro scale is limited by the size of a structure, and simplifications of models in structural integrity analysis must be respected.

Presented approaches can be considered as a further and a very detailed extension of previously developed crack significance assessment, including practical application, by involved high level of theoretically based knowledge gathered at different scales, but there are other influencing factors of high importance for material response and behaviour under loading. One is transition of properties at nano-scale, indicating the material does not behave in fact as expected, a problem similar to the discovered nil-ductility transition temperature of steel, mentioned already (in fact it does not treat the situation at the crack tip). In yet another peculiarity of the nano-world, researchers at the National Institute of

Standards and Technology (NIST) and the University of Maryland-College Park have discovered that materials such as silica, that are brittle in bulk form, behave as ductile as gold at nano-scale, /59/, Fig. 40. Their results may affect the design of future nanostructures. Pradeep Namboodiri, Doo-In Kim and colleagues from NIST first demonstrated the latest incongruity between macro and micro worlds with direct experimental evidence for nano-scale ductility. Later on, NIST researchers Takumi Hawa and Michael Zachariah and guest researcher Brian Henz shared the insights they gained into the phenomenon through their computer simulations of nano-particle aggregates. At macro-scale, the point at which a material will fail or break depends on its ability to maintain its shape when stressed. Atoms of ductile substances are able to shuffle around and remain cohesive for much longer than their brittle cousins, which contain faint structural flaws that act as failure points under stress. At nano-scale, these structural flaws do not exist, and hence the materials regarding the strength are nearly “ideal.” In addition, these objects are so small that most of the atoms that comprise them reside on the surface. According to Namboodiri and Kim, the properties of surface atoms, which are more mobile because they are not bounded on all sides, dominate at nano-scale. This dominance gives an otherwise brittle material such as silica its counterintuitive fracture characteristics. Hence, they claim that “the terms ‘brittle’ and ‘ductile’ are macroscopic terminology”, probably not applicable at the nano-scale”. Accordingly, since crack size is defined at macro- and micro-level, its definition for applications at lower levels should be modified, what is also necessary for stress and strength, and many connected terms, as brittle and ductile, including also toughness, /59/.

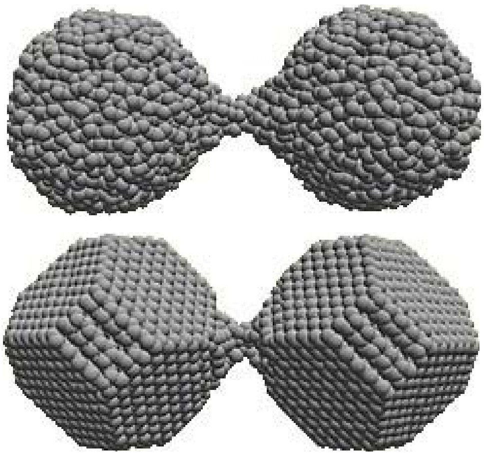

Figure 40. NIST researchers have shown that silica that are brittle in bulk, exhibit ductile behaviour at the nanoscale. Computer simulations demonstrate material extension and necking that occurs during the separation of amorphous (top) and crystalline (bottom) silica nanoparticles, /59/.

Slika 40. Istraživači NIST su pokazali da silicijum dioksid, koji je masi pokazuje duktilno ponašanje na nano nivou. Kompjuterska simulacija pokazuje istezanje materijala i pojavu vrata kod razdvajanja amorfnih (gore) i kristalnih (dole) nano čestica silicijum dioksida, /59/

Using an atomic force microscope (AFM), Kim and Namboodiri were able to look more closely at interfacial fracture than has been done before at the nano-scale. They found that the silica will stretch as much as gold or silver and will continue to deform beyond the point that would be predicted using its bulk-scale properties. Hawa, Henz and Zachariah’s simulations reaffirmed their study and added some additional details. They showed that both nano-particle size and morphology, whether the material is basically crystalline or amorphous, for example, have an effect on the observed ductility and tensile strength because those factors influence the mobility of surface atoms. In the simulations, the smaller the particles in the aggregate, the more ductile the material behaves. Crystalline structures exhibited greater strength when stressed and deformed long after the critical yield point is observed macroscopically.

To understand better the approaches to damage and failure of structures is important for structural integrity, and their eventual application at nano-scale, four keywords require some consideration: structure, integrity, crack and fracture. Structure is considered here as a composition designed and produced for requested purpose and use. It needs to save its integrity in the designed life even in the case of a present defect, as in the most dangerous form as a crack, which is considered as locally separated material. The fracture process is characterised by a growing crack. Since the crack is considered as a void area with a boundary, its tip exists as a singularity, and for that tip is not a keyword, although the region ahead of the crack tip is of prime interest for fracture development. These definitions, open to criticizing and commenting, are accepted as a convention.

DISCUSSION

Presented examples allow to classify structures and objects into three groups. In the first group are structures of low sensitivity to cracking and crack development. The main reason is that the applied load does not produce tensile strength and crack opening (mode I). Such structures save their integrity for a very long time period and mainly are monumental objects, of stone, from the ancient era. These are now UNESCO historical heritage sites, as pyramids, the Parthenon, the Leptis Magna location. Today, they are attractive touristic locations, with little restoration. In the same group are also some structures made of metal, as the Eiffel Tower and the Iron Bridge. The Eiffel Tower has preserved its integrity thanks to proper maintenance and still is an attractive monument of Paris. The Iron Bridge is known as a structure with cracking induced at the time of construction that did not develop during use.

The second group includes structures, mainly metallic, sensitive to cracking and crack development. Presented fracture case studies, sometimes catastrophic, are examples of structures of the second group. Typical, huge structures (as a rotor excavator, sea platforms), pressure equipment and boilers, rotating machines, bridges. They are a danger in service and thus, structural integrity assessment is a strict request, starting from the design phase up to the end of operating life. Maintenance and repair of such objects is important for structural integrity, and they are induced in manuals, and also in codes, standards and directives.

The third group represents two specific objects, huge buildings, as the Burj Khalifa and similar, and minor nano structures, for which structural integrity comprises reliability and functionality, in addition to elementary integrity. The Burj Khalifa is in fact a complex system, consisting of a series of subsystems, and each subsystem requires proven structural integrity. Nanomaterials and nanostructures require extended investigation since they exhibit behaviour that is not consistent with material characteristics defined for materials at macro and micro levels. In both cases, some redefinition of structural integrity terms is necessary.

Structural integrity assessment is based on inevitable assumptions and simplifications. In that sense the problem can be considered as a specific approach to structural reliability. A basic presumption is the homogeneous microstructure, acceptable in some cases at macro- and eventually at micro level, but it cannot be applicable with a certainty at nano level. This assumption is far from real even at macro level, i.e. for welded structures.

A relatively long way has past to understand fracture of structural components and its mechanisms, /60/. In the beginning of systematic analysis, the knowledge about this matter was limited and the problem is considered by gathering new experience and developing new theories, experimental and numerical procedures. But a lot has to be done more, entering the nano level. It is not an easy task to make the conclusion on this fast developing matter. Instead, some considerations from /59/ are quoted: "At the macro scale, the point at which a material will fail or break depends on its ability to maintain its shape when stressed. Atoms of ductile substances can shuffle around and remain cohesive longer than brittle, which contain structural flaws acting as failure points. At the nano scale, these structural flaws do not exist. These objects are so small that most of the atoms reside on the surface. According to Namboodiri and Kim, the properties of more mobile surface atoms, not bounded on all sides, dominate at the nano scale. This dominance gives, an otherwise brittle material (silica), its counterintuitive fracture properties".

The story about fracture, crack and crack tip is more and more far from its end by gathering more knowledge and applying more sophisticated approaches, thanks to experimental and numerical methods, such as atomic force microscope and powerful computers and software. Considering crack surfaces as typical kinds of interfaces, it is necessary to find out actual limits that can help to understand the fracturing process at different scales. Provisional and temporary conclusions on the considered matter is explained probably in the best way in /61/: "We can distinguish between interfaces in general and nano-interfaces as follows: Typically, an interface separates two bulk phases; we define, consistent with the above definition, a nano-interface as one in which the extent of one or more of the phases being separated by the interfaces is nanoscopic. In nano-interfaces we include nano-interconnects, which join two or more structures at the nano-scale. For nanointerfaces, traditional surface science is generally not applicable."

It is clear from fracture case study /2/ that some material property might be unknown and that the actual problem could be solved only if this property is recognised, characterized and specified for given circumstances. This could be more pronounced in the case of fatigue (e.g. low cycle fatigue) or in the case of creep. Having in mind the development stage of a nanostructure, one can expect more uncertainties in the case of nanomaterials, suggested in the performed research of ductile behaviour found at nano level of a material brittle at macro level, /59/.

Stress, defined as the ratio of load and size of loaded area, is the fundamental value in engineering calculations. So defined, stress became the most used parameter in structures for analysis and comparison with characterized properties of material strength. However, the area is of final size at macro level under accepted assumptions, and this is not the case at nano level. While using the fracture atomic model (Fig. 27), stress at nano level could be considered as the sum of atomic forces rather than through area, difficult to be defined in the model with a distinct atomic arrangement.

The defects, including cracks, cannot be considered in the same way in macro and in nano structures. It is not possible to interpret crack tip and its severity in nanomaterial, since in this case the scale is on similar level, requiring for a different definition of stress concentration, if any. It is likely that an another approach for calculating loaded components is necessary at nano level, but before that or at the same time new properties should be discovered, similarly as in the case of the failed ship, /2/.

Nowadays, experimental techniques and equipment with computers and software, have achieved an impressive level that almost everything can be modelled and analysed virtually (Fig. 38). But that implies a necessary change of approach in regards to security, safety and reliability, expressed already by the number of scientists and published papers. In this situation the problem how to transfer the fracture process characteristics to different scales has become significant, /33, 62, 63/.

CONCLUSION

Although structural integrity assessment is well defined, accepted and adopted for practical application, there are still regions in which its application is questionable due to shortage in knowledge and experience. Hence, the problem of structural integrity needs to be opened in order to follow further developments in science and engineering.

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