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Subject review

Structural Integrity - Historical Context

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Abstract: In this paper the focus is on a historic context of a few milestones in the development of structural integrity, which closely follow development of human civilization. Starting from the Great Pyramids in ancient Egypt, this story leads us through the history of stone, concrete and metal constructions as follows: Hagia Sophia, stone (Mostar) and iron (Shropshire) bridges, skyscrapers (Eiffel tower, Burj Khalifa) and sky reaching airplanes (Airbus A380). In each case, the most important aspects of structural integrity are presented, as well as an analysis of driving force for its creation. This paper is dedicated to the memory of Prof. Stojan Sedmak (1929-2014), father of the fracture mechanics in South East Europe and the author of the original version of the paper, written 10 years ago with different focus, [1].

Keywords: construction material; driving force; historical context; structural integrity

1 INTRODUCTION

Historical and archaeological data show that people even from prehistoric times built various structures, including places to live, bridges, temples, amphitheatres, dams, canals and roads. Building materials have changed throughout history and some of the ancient structures are still considered exceptional today. The history of structures overlaps with the history of construction, metallurgy, carpentry, and many other areas. Some early building materials, such as tree branches, leaves and animal skins, were short-lived. The more durable natural materials were stone, clay, wood and brick, whereas modern, synthetic materials, such as concrete, metals and plastics, not to mention composites, are dominantly used. With the development of new materials and design concepts, man has mastered the ways of making challenging constructions fulfilling ever increasing structural integrity requirements.

Term "structural integrity" describes how fracture mechanics principles can be used to prevent a failure, [1]. It heavily relies on fracture mechanics as a scientific and engineering discipline, first introduced to describe failure in service [2], and then applied to prevent a failure, leading to the notion of structural integrity. Few objects preserved integrity during centuries, and nowadays they are valuable historical monuments, following development of civilization.

In this article significance and applicability of structural integrity from the historical point of view is considered. By that we mean a specific and original analysis of historical context in which some of the most important constructions in human history have been built. Toward this aim Great pyramids, Hagia Sophia, bridges starting from the stone ones to the metallic ones, skyscrapers like Eiffel tower, Empire State Building, Burj Khalifa and finally, sky reaching aeronautical structures like Airbus A380, are analysed both from structural integrity and historical point of view.

2 SIGNIFICANCE OF STRUCTURAL INTEGRITY ASSESSMENT IN HISTORICAL CONTEXT

A historical overview of the development of engineering structures enables better understanding of the significance of structura integrity assessment, [1]. Toward this aim, some of the most significant achievements in human history are selected and considered in more details, both from structural integrity and historical points of view.

2.1 The Great Pyramids of Giza

The Great pyramids of Giza are the only surviving wonder of the Seven Wonders of the ancient era, [3], Fig. 1. They were built 4.5 millennia ago and served as pharaoh tombs. The largest one is the pyramid of Cheops with its original height of 146.6 m, the highest man-made structure until 1880-ies. The exterior of polished limestone is mostly removed to be used in the construction of other buildings, so its height today is 137 m.

Figure 1 The Great pyramids of Giza, [3].

Figure 2 Blocks that look like being cast

Scientists still can't explain how 2.3 million stone blocks with an average weight of 2.5 tons were put together to build the Great Pyramid [3-7]. One of relatively new theories, proposed by Davidovits, is that the pyramids were cast in situ using granular limestone aggregate and an alkali-based binder, [8]. To investigate this theory, Michael

Barsoum and his research team used SEM and TEM, to prove this theory could also explain how the Pyramid tops were built, Fig. 2, [9].

Historic context of Great pyramids is not completely clear, since we still do not know if they were just tombs or had more functions and/or symbolic meaning. In any case they were erected toward the heaven and certainly demonstrated the almighty power of a pharaoh, who ordered and inspired man force in Egypt to construct unprecedented structure, which remained the highest man-made object on Earth until the late XIX century.

2.2 Hagia Sophia Dome

In the mid VI century A.D., Justinian I inaugurated the construction of a basilica in Constantinopolis, nowadays Istanbul, larger and more majestic than its predecessors, [10-12]. The main feature of Hagia Sophia is the dome, made of stone, one of the largest in the world. The first one, made during the reign of Justinian I, collapsed, while the second one, ordered by his suceedor Justinian II, still stands, providing important lecture in design and structural integrity. Namely, earthquakes in 553 and 557 initiated cracks in the main dome and eastern semi-dome, leading to its collapse during the subsequent earthquake on 7 May 558, [13], mainly due to the excessive shear load of the dome, which was too flat to withhold it. As a consequence, the piers could not sustain any more the weight of the dome. Restoration started immediately, with lighter materials and hemispherical shape, giving Hagia Sophia its current interior height of 55.6 m and the present form, Fig. 3. The most important feature are pendentives enabling optimal distribution of weight load from the circular dome to the rectangular supporting structure, comprising 4 large columns, in a form of the Roman arch. Later on, additional supporting elements were added on each of the 4 sides.

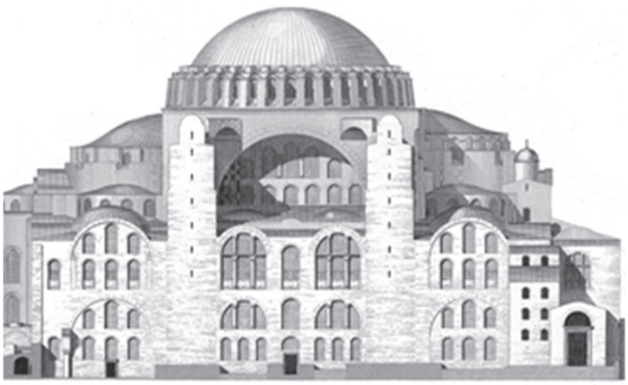

Figure 3 Hagia Sophia, [7]

After seeing the completed masterpiece, Justinian II reportedly said: "Salomon, I have surpassed thee", [14]. Obviously, driving force to build such a magnificent church was not only the usual historic context of demonstrating the power and "reaching" the heights of God, but also competition with historic rivals, including Rome Pantheon and Salomon temple. In terms of dome diameter, Hagia Sophia did not surpass the Rome Pantheon, since its dome with diameter 43.3 m, built more than 500 years before Hagia Sophia, still presents the world largest self-supported concrete object in the world, Fig. 4, [15]. Anyhow, one should notice that Hagia Sophia's dome was the first one to lie on a square support, thanks to the ingenious design with pendentives, as already described.

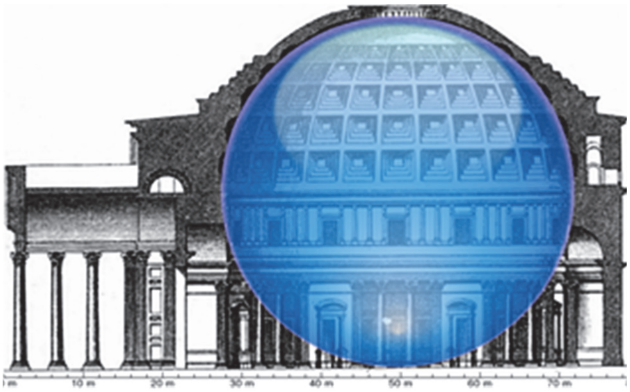

Figure 4 Pantheon cross-section with 43.3-metre diameter sphere fitting under its dome, [10]

More details about geometrical aspects of design of domes can be found in [16], where St. Peters Basilica dome was analysed in details from this point of view. Even though it was made fifteen Centuries after Rome Pantheon, its dome is still a bit smaller (41.5 m). One can notice that both domes were surpassed by the Florence Cathedral's dome (44 m), but it was built of bricks in a different way. In modern times, only reinforced or prestressed concrete dome surpassed all of them, e.g. Hall No. 1 of the Belgrade Fair in Serbia, 1957, with the span 109 m, designed by Branko Zezelj, [17], proving the importance and dominance of new materials and ingenuity of engineers who use them to reach new horizons in design and construction.

2.3 Bridges from Wood, Stone and Concrete to Metallic Age

Bridges are not only links between two banks, but also between different times and materials, i.e. between wood, stone, concrete, iron and steel. In any case, they are made and still being made to connect people and to some extend to show ingenuity of their builders and power of acting rulers. The first bridges were made of stone and wood, the simplest ones being wooden boulders placed over a stream. The oldest stone bridge still in use, [18], often called Caravan Bridge, dating from 850 BC, was built in Izmir, to cross River Meles, Fig. 5. One can see that the so-called Roman arch was actually used even before the Roman Empire.

Figure 5 The oldest stone bridge in the world, Izmir, [13]

Anyhow, it was the Trajan's bridge over Danube that made the history as the first bridge with significant span, since it connected banks of the lower Danube, Fig. 6, representing a remarkable achievement in the early II century A. D. It was a Roman segmental arch bridge, total length 1135 m, one of the greatest achievements in Roman engineering, [19]. Apollodorus of Damascus, engineer in charge, used wooden arches with the span of 38 m, set on twenty brick masonry pillars, mortar, and pozzolana cement, [19-22]. It was built between years 103 and 105, using the wooden caisson for piers, Fig. 6. Later on, it was surpassed in length by the Constantine's Bridge, not a well-known structure with total length 2,437 m, built also at the lower Danube, in the same way, using stone piers and wooden arches. In any case, wooden construction could not survive for a long time in a harsh environment and other detrimental influences, so both Roman bridges over Danube were destroyed before the end of the IV century. In both cases the driving force was a military one - to enable the conquest of Dacia.

Figure 6 Trajan's bridge schematic presentation (top), remains of stone pier (bottom)

Figure 7 Stone bridge in Mostar, [23]

Another important achievement was from the XVI century, when the old bridge in Mostar, Herzegovina, Fig. 7, was built by MimarHayruddin to replace a wooden bridge, [23-27]. Construction took place between 1557 and 1566, according to the inscription on the bridge. Other than that, nothing is preserved in writing. It is thought to have been made from mortar made with egg whites. It was the widest man-made arch in the world at the time, with the span 30 m.

As for the structural integrity, it was not well explained until the early fifties of XX century. Namely, according to calculations previously made, the bridge structure was not capable of sustaining its own weight, so it was a bit of a mystery before young scientists, Aleksandar Vesic, from the University of Belgrade, proved in his D.Sc. thesis that the bridge was hollow and thus much lighter than previously thought, [28]. Nevertheless, to get longer span and larger bridges, the usage of metal, i.e. iron and steel was inevitable, as shown by the following example.

The Iron Bridge, [29, 30], over the River Severn in Shropshire, England, Fig. 8a, was the first cast iron arch bridge, since cast iron was previously far too expensive to be used for structures like this. Once a new blast furnace nearby became operational, the cost was lowered significantly and engineers were able to design a bridge using new material, as an important step forward in reaching much larger distances between two banks. It actually happened in the eight decade of the XVIII century, at the beginning of the Industrial revolution, when Thomas Pritchard made plans to use cast iron for the first time to build a bridge. According to his plans, Abraham Darby III, an ironmaster from Coalbrookdale, produced cast iron and built the bridge, to be opened on January 1st, 1781. One can say that man's ingenuity, driven by demands of a new era, set a necessary historical stage.

Figure 8 The Iron Bridge (top), and cracked supports (bottom), [29]

Only a few years after the construction, ground movement initiated cracks in the masonry bridge abutments, Fig. 8b. Nowadays present cracks may date from this time, although some of them are probably casting cracks. Few of them were pinned with wrought iron straps, while others are left free. By 1802, the southern stone abutment was replaced with wooden arches, and later on with iron arches. So, its integrity has been preserved with just a few repairs even though serious cracks appeared long time ago.

Later on, one could witness spectacular constructions made of prestressed or reinforced concrete, or high quality steel, or both, with total length of over 100 km.

2.4 Eiffel Tower

The Eiffel Tower, Fig. 9, made of iron, and thus nick-named "La dame de fer", is located on the Champ de Mars in Paris. It was built in 1889 as the entrance arch for the World Exhibition, being the highest constructed civil engineering object until 1930 with its 324 m height. It may sway in the wind up to 6-7 cm without jeopardizing its structural integrity.

Figure 9 Eiffel Tower, "La dame de fer"

Eiffel understood the importance of wind forces as the most critical loading for the tallest structure in the world at the time, so he said: "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", [31-33]. Eiffel explained his calculations, leading to an exponential shape, in two steps: (1) a base, standing on 4 main pillars, bonded and extended with a lighter batter as the second floor, Fig. 9; (2) a tower firmly attached atop.

The Tower is made of puddle iron, assembled using fabricated cast iron parts, including 16 truss supports. The puddle iron that makes up the Eiffel Tower's structure came from the Pompey forges, East of France. The iron plates and beams produced through the puddling process were then preassembled in the Eiffel factories in Levallois Perret using rivets. It was the time of the Industrial Revolution, when steam engines, circular saws, machine-cut nails and other new technologies, improved construction capabilities.

Historical context is a bit similar to the previous one (bridges), reflecting man's ingenuity, but with a significant difference in its aim. Namely, bridges were a historical necessity for a growing economy, whereas the Eiffel tower was aimed to impress the whole world with a technical achievement reflecting more the power of France than anything else. Actually, it was scheduled for disassembling in 1909, but fortunately it did not happen. Later on, it became an iconic image of Paris and France, attracting tourists at very large numbers and thus contributing significantly to the economy!

2.5 "Race into the sky" - Empire State Building, Burj Khalifa

The late 1920s were a period when the New York economy was booming like never before. It was also the time of the second industrial revolution, with new technological achievements in the form of elevators and cranes, hot rivets, power tools and other equipment that enabled the construction of tall buildings, such as the Empire State Building, Fig. 10.

Figure 10 Empire State Building

Empire State Building was constructed in New York City, as a direct consequence of the race with the 40 Wall Street's Bank of Manhattan and Chrysler building to make as tall building as possible [34-36]. It was the first of a kind with the supporting structure made of steel, joined by bolt. Several important historical aspects were present, already mentioned competition of ambitious people and corporations, and development of steel production and joining technology. In addition, economy was an important issue, but that was not a simple case, since the construction coincided with the Great Depression. Not surprisingly, a nickname "Empty State Building" was actual for 20 years, before the Empire State Building started making profit. Finally, power demonstration is obvious by the name itself, taken as the nickname of New York state. One should notice that steel was used as the support structure, if not for the first time, certainly one of the first and the most important at the time. Welding was yet to be introduced in engineering practice, so joining with hot bolts was used to connect bearing supporting elements.

Other more recent new technologies and computer-aided developments in design, materials and technology enabled the construction of Burj Khalifa (Fig. 11) in Dubai, [37-39], declared as being the "Tallest Building in the World" at its opening in 2010. With its 828 m, it is the highest construction ever built. The 280,000 m^2 reinforced concrete construction is predominantly used for residential and office purpose, but also includes hotel and retail shops. The main task was to make an efficient building occupying as little ground space as possible, while maintaining the integrity of the initial design concept against strong winds.

Figure 11 Burj Khalifa (828 m), [37]

Ingenious design of Burj Khalifa included a tri-axial, "Y" shaped floor plan, formed by three individual wings connected to a central core. As the Tower rises, one wing at each tier sets back in a beautiful spiralling shape, further emphasizing its height. Anyhow, the main purpose of the spiralling "Y" shaped plan is to reduce wind forces on the Tower, as well as to keep the structure simple and to foster constructability. The result is extremely stiff construction, both in bending and torsion. One should also notice that the gravity load resisting system was used to maximize its role in resisting lateral loads.

For the first time, the tubular system with steel supporting construction was used, as invented by Khan, [38-39], enabling construction with only half the amount of steel, compared to the Empire State Building. Khan's "tube concept", using all the exterior wall perimeter structure of a building to simulate a thin-walled tube, revolutionized tall building design.

Historical context is strongly related to the decision of the ruler of Dubai to overcome economy problems caused by the reduction of oil quantities by diversifying the economies and to give Dubai international recognition. The building was named after the ruler of Abu Dhabi and the President of the United Arab Emirates, Caliph bin Zayed Al Nahyan, who lent money to Dubai to pay the debts under construction. When construction began, the goal was set to construct the tallest building in the world with design in accordance with the regional Islamic architecture. At the same time, it is a commercial building with hotels, shops, restaurants, offices, residential areas.

2.6 Aeronautical Engineering

However tall, a building cannot reach the sky. To do so, one has to fly, which brings about different and equally challenging aspects of design and use of material. As a matter of fact, probably nothing else was such an inspiration for engineers as to tackle aviation problems using new design approaches and new materials. The first attempt to make a passenger airplane with jet engines, back in fifties of XX century, the famous Comet series (Great Britain), was stopped due to several failures, **[xx]**. It was yet to be discovered that fatigue cracking was the major problem due to underestimated stress concentration. New methods were needed for calculation, so the Finite Element Method was introduced, [40], as well as extensive experimental investigation of fatigue crack growth, providing the famous exponential equation, known as the Paris law, [41].

Figure 12 Airbus A380, the world's largest passenger airliner, [42]

In addition, new materials were used, equally strong, but much lighter than steel, starting with Aluminum alloys and more recently partly replaced by composites. As the result, the first Boing (USA) took over for decades and made the first jumbo jet in ever increasing race to handle more and more passengers, until Europe's Airbus launched A380, Fig. 12, about a decade ago, as the world's largest passenger airliner, representing one of the finest achievements in the history of structural integrity. It was a long way to success, followed by occasional failures and extensive testing, [42-49]. Driving force was economy, but in this case, contrary to bridges that still need to be longer and longer, economy actually stopped further progress and even starts to jeopardize the existing achievement. So, the historical context in this case is definitely complex and even unpredictable.

3 CONCLUSIONS

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 put in historical context in order to follow and predict its further development, since history often hides inspiration for new achievements.

Historical aspects of presented structural integrity examples indicate that these extraordinary achievements are basically driven by the need to show the power or by economy, or by both. In any case human ingenuity was needed to perform the task, often in accordance with the well-known Latin saying: per aspera ad astra!

4 REFERENCES

[1] Sedmak, S., Radakovic, Z., Milovic, Lj., & Svetel, I. (2012). Significance and applicability of structural integrity assessment. *Structural Integrity and Life*, *12*(1), 3-30.
[2] Sedmak, S., Grabulov, V., &Momčilović, D. (2009). Chronology of lost structural integrity initiated from manufacturing defects in welded structures. *Structural Integrity and Life*, *9*(1), 39-50.
[3] Arnold, D. (1991). *Building in Egypt: Pharaonic Stone Masonry*. Oxford: Oxford University Press.
[4] Verner, M. (2001). *The Pyramids: Their Archeology and History*. London: Atlantic Books.
[5] Lehner, M. (1997). *The Complete Pyramids: Solving the Ancient Mysteries*. London: Thames & Hudson.
[6] Mendelssohn, K. (1974). *The Riddle of the Pyramids*. London: Thames & Hudson;
[7] Parry, D. (2004). *Engineering the Pyramids*. London: Sutton.
[8] Davidovits, J. & Morris, M. (1988). *The Pyramids: An Enigma Solved*. New York: Hippocrene Books.
[9] See http://www.materials.drexel.edu/Pyramids/
[10] Kaldellis, A. (2013). The Making of Hagia Sophia and the Last Pagansof New Rome. *Journal of Late Antiquity*, *6*(2), 347-366. https://doi.org/10.1353/jla.2013.0019
[11] Mainstone, J. R. (2001). *Hagia Sophia: Architecture, Structure and LiturgyofJustinian's Great Church*. London: Thames & Hudson;
[12] Dark, K. & Kostenec, J. (2019).*Hagia Sophia in Context: An Archaeological Re-Examination of the Cathedral of Byzantine Constantinople*. Oxford: Oxbow Books.
[13] Janin, R. (1950). *Constantinople Byzantine* (in French) (1st ed.). Paris: Institut Français d'Études Byzantines.
[14] Herrin, J. (2007). *The Surprising Life of a Medieval Empire.* London: Penguin.
[15] MacDonald, L.W. (1976). *Pantheon: Design, Meaning and Progeny*. Cambridge Mass.: Harvard University Press.
[16] Milosavljević, P., Grujić, G., & Đuričković, V. (2017). Ruggiero Boscovich and Application of Plato's - Geometrical Number Concept in Damage Analysis and Repair of the Dome of St. Peter's Basilica in Vatican City. *Structural Integrity and Life*, *17*(1), 74-84.
[17] Jelić, M. (2017). Common Characteristics of Main Contributions of Roger Boscovich, Milutin Milanković and Branko Žeželj to the Development of Civil Engineering. *Structural Integrity and Life*, *17*(2), 157-169.
[18] https://www.oldest.org/structures/bridges/
[19] Fernández, T. L. (2003). *Bridge Engineering - Global Perspective*. Thomas Telford Publishing.
[20] O'Connor, C. (1993). *Roman Bridges*. Cambridge: Cambridge University Press.
[21] Ulrich, R. B. (2007). *Roman Woodworking*. New Haven: Yale University Press.
[22] Griggs, F. E. (2007) Trajan's Bridge: The World's First Long-Span Wooden Bridge.*Civil Engineering Practice*, *22*(1), 19-50.
[23] See https://en.wikipedia.org/wiki/Stari_Most
[24] Andrejević, A. (1990). Neimar Hajredin i njegov rad u Hercegovini (in Serbian). *Hercegovina, časopis za kulturno i istorijsko nasljeđe*, *7/8*, 39-51.
[25] Aslanapa, O. (2012). *ustād Khayr al-Dīn in: Encyclopaedia of Islam*, 2nd Edition. Edited by: P. Bearman, Th. Bianquis, C.E. Bosworth, E. van Donzel, W.P. Heinrichs
[26] Morkoc B. S. (2010). *A Study of Ottoman Narratives on Architecture: Text, Context, and Hermeneutics*. Bethesda, Dublin, Palo Alto: Academica Press;
[27] Goodwin, G. (1971). *A History of Ottoman Architecture*. London: Thames and Hudson.
[28] Vesic, A. (1956). Doctoral thesis (in Serbian), University of Belgrade.
[29] Powell, J. (2002). *Darby, Abraham, III, A Biographical Dictionary of Civil Engineers in Great Britain and Ireland*, vol.1: 1500-1830. ed. By Skempton A. W., Chrimes M. M., et al. London: Thomas Telford.
[30] Cipolla M. C. (ed.) (1973). *The Industrial Revolution, The Fontana Economic History of Europe*. London: Collins and Fontana Books.
[31] Woog, A. (2014). *The Eiffel Tower.* San Diego: Reference Point Press.
[32] Jones, J. (2009). *Eiffel's Tower, and theWorld's Fair Where Buffalo Bill Beguiled Paris, the Artists Quarreled, and Thomas Edison Became a Count*. New York: Viking Penguin.
[33] Tombs, R. (1996). *France 1814-1914.* Harlow: Longman.
[34] Tauranac, J. (1996). *The Empire State Building: The Making of a Landmark.* New York: St. Martin's Griffin.
[35] Martin, D. (1994). *The Architecture of New York City: Histories and Views of Important Structures, Sites, and Symbols*. New York: Wiley.
[36] Stern A. M. R., Gilmartin G., & Mellins T. (1987). *New York 1930: Architecture and Urbanism Between Two World Wars.* New York: Rizzoli.
[37] See https://www.som.com/projects/burj-khalifa/
[38] Reisz, T. (2021). *Showpiece City: How Architecture made Dubai*. Stanford: Stanford University Press.
[39] Ali, M. M. (2001). Evolution of Concrete Skyscrapers: from Ingalls to Jin Mao. *Electronic Journal of Structural Engineering*, *1*(1), 2-14.
[40] Turner, M. J., Clough, R. W., Martin H. C., & Topp, L. J. (1956). Stiffness and Deflection Analysis of Complex Structures. *Journal of theAeronautical Sciences*, *23*(9), 805-823. https://doi.org/10.2514/8.3664
[41] Paris, P. C. & Erdogan, F. (1963). A critical analysis of crack propagation laws. *Journal of Basic Engineering*, 85D, 528-533.
[42] See http://en.wikipedia.org/wiki/Airbus_A380
[43] Wanhill, R. (2009). Some notable aircraft service failures investigated by the National Aerospace Laboratory (NLR). *Structural Integrity and Life*, *9*(2), 1-88.

[44] Barter, S.A., Molent, L., White, P., & Dixon, B. (2009). Recent Australian full-scale F/A-18 fatigue tests. *Structural Integrity and Life*, *9*(2), 89-112.
[45] Posavljak, S., (2009), Damages computation of aircraft engine disks. *Structural Integrity and Life*, *9*(2), 113-124.
[46] Grbović, A., Sedmak, A., Kastratović, G., Petrašinović, D., Vidanović, N., & Sghayer, A. (2019). Effect of laser beam welded reinforcement on integral skin panel fatigue life. *Engineering Failure Analysis*, 101, 383-393. https://doi.org/10.1016/j.engfailanal.2019.03.029
[47] Sghayer, A., Grbović, A., Sedmak, A., Dinulović, M., Grozdanovic, I., Sedmak, S., & Petrovski, B. (2018). Experimental and numerical analysis of fatigue crack growth in integral skin-stringer panels. *Tehnicki Vjesnik*, *25*(3),785-791. https://doi.org/10.17559/TV-20170308110329
[48] Sghayer, A., Grbović, A., Sedmak, A., Dinulović, M., Doncheva, E., & Petrovski, B. (2017). Fatigue lifeanalysisofthe integral skin-stringer panel using XFEM. *Structural Integrity and Life*, *17*(1), 7-10.
[49] Eldwaib, K., Grbovic, A., Sedmak, A., Kastratovic, G., Petrasinovic, D., & Sedmak, S. (2018). Fatigue Life Estimation of Damaged Integral Wing Spar Using xFEM. *Technical Gazette*, *25*(6), 1837-1842. https://doi.org/10.17559/TV-20171007105350
[50] Aldarwish, M., Grbovic, A., Kastratovic, G., Sedmak, A., & Lazic, M. (2018). Stress Intensity Factors Evaluation at Tips of Multi-Site Cracks in Unstiffened 2024-T3 Aluminium Panel Using XFEM. *Technical Gazette*, *25*(6), 1616-1622. https://doi.org/10.17559/TV-20170309133824

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