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Application of the State-Of-The Art Engineering Methods in Nautical Archaeology

Abstract

Modern interdisciplinary projects are connecting researchers from seemingly unrelated fields, like naval engineering and archaeology. However, archaeological remnants of the present days, such as ancient ships and ceramic transport containers, were created by engineers and artisans of the past. It is therefore meaningful to consider their function and construction from an engineering point of view, complementing the archaeological research. One track of the interdisciplinary project Archaeology of Adriatic Shipbuilding and Seafaring (AdriaS), founded by the Croatian Science Foundation, aims at better understanding of structural behaviour of the ancient seaborne structures, made of wood and ceramics. In addition, a reverse engineering method is considered in the analysis of underwater archaeological sites, by the simulation of capsizing of ancient ship. This paper presents the possibilities and limitation of the application of the state-of-the-art engineering methods in nautical archaeology. It focuses on the analysis of wooden and ceramics structures, particularly through the identification of open questions, and exploitation of proper material models. Moreover, it presents the complex fluid-structure interaction analysis of a ship capsizing event as a possible engineering tool for testing hypothesis.

Keywords: nonlinear FEM, fluid-structure analysis, ancient ships, capsizing, amphorae, nautical archaeology

1. Introduction

Nautical archaeology is a clearly defined and structured archaeological discipline (Pomey, Rieth 2005), which focuses on the research on shipbuilding and seafaring evidence from the past. As such, nautical archaeologists study shipwrecks, ship cargo, underwater and coastal structures made by humans (e.g. piers, waterfronts, slipways, shipsheds, harbours etc.). Performing research on the material that can be dated to many millennia before present is far from straightforward – not only that the material remains are usually scarce and changed by the natural degradation processes, but also the entire landscape and seascape may have been quite different, as the consequence of natural forces or human impact. Therefore, nautical archaeologists need to have a waste knowledge about the factors that may affect their conclusions and theories. When nautical archaeology focuses mainly to the study of past shipwrecks, two main aspects may be distinguished.

The first one is an essential need of extremely careful, methodical and systematic excavation of the complex shipwreck sites. In many cases they provide an extraordinary number of artefacts. What is found on the seabed, besides the remnants of the wooden hull structure, sometimes encompasses impressive collection of artefacts from the ship's equipment, armament and cargo (see the example of the Gnalić Shipwreck in Radić Rossi, Nicolardi, Batur 2016).

Second aspect is the interpretation of the results, which is particularly related to the attempt of the plausible reconstruction of the ship structure, and its performance on the sea. Finally, it aims at reconstruction of the evolution of shipbuilding and seafaring through the past. In this phase the historians can highly contribute to the research, through the identification of specific ships or ship types in the written sources (see the example of the Gnalić Shipwreck in Radić Rossi *et al.* 2013). Unfortunately, detailed information is available just for relatively recent shipwrecks, and moving further back to the past requires skilled analysis of the existing data and careful theoretical approach.

Although nautical archaeology is already a well established discipline, there is still significant room for its development and reach. In recent times, it benefits from the availability of sophisticated instrumentation, such as sonars, autonomous underwater vehicles, photogrammetric recording tools, which provide accurate 3D models of the sites etc. However, the application of the modern engineering tools for the analysis of the nautical archaeology records and scenarios is far from common.

Archaeology of Adriatic Shipbuilding and Seafaring Project (AdriaS), supported by the Croatian Science Foundation, is an interdisciplinary project, initiated in June 2015, which aims to combine the knowledge of nautical archaeologists, historians, philosophers and engineers in a systematic research on the technological development of shipbuilding and seafaring in the Adriatic Sea. This paper describes the approach elaborated by the authors in identifying the open questions, and how to address them from the engineering point of view.

In the next three chapters, we briefly present the following issues:

- ceramics as structural material, through the study of amphorae as ceramic transport containers for various goods, used over past several millennia for seaborne trade all over the Mediterranean;
- wood as a structural material, and open questions related to wooden ship construction;
- ship sinking scenario, modelled using the state-of-the-art engineering methods, as an engineering tool for testing hypothesis.

2. Ceramics as a structural material

Amphorae are iconic ceramics containers that have been extensively used through most of the ancient maritime history. Amphorae are made locally, from the available clay, and baked skilfully to obtain desired shape and quality. They were used for the transport of wine, olive oil, salted fish products as well as many other merchandises.

Amphorae are found in a variety of shapes and sizes, from the small to the very large ones, having a transporting capacity from around 5 to 100 litres. The average capacity of an amphora was expressed by the unity of measure of the same name, which in Greek period was 19,5 l, while in Roman increased to 26,2 l. Upon looking at the shape and size of some of the most common amphorae, two questions arise: how were these amphorae handled, and what was the main reason for the evolution of their shape, especially in regard to the spike on their bottom.

Handling the amphorae is not a trivial problem. Although there is no doubt that ancient people knew how to handle them skilfully, the fact remains that amphorae are far from perfect packaging product: not only that they are unstable from every point of view, but they are made of material that may suddenly crack due to the impact with the other hard surfaces, especially where concentration of stresses naturally occurs.

Several investigations were performed in the attempt to understand the structural strength of the amphorae. Radić Rossi *et al.* (2004) performed a research on the origin and function of the amphora's spike. Kilikoglou *et al.* (2002) presented a quantitative model for predicting the failure of ceramic vessels under any possible loading condition. Stresses and strains of ceramic vessels were examined by finite element method.

Other than this, very little research is done. On the other hand, many questions remain to be solved, such as were there any structural strength related reasons for the amphora shape variation, or how exactly where the amphorae placed and secured within the cargo hold of the antient ship (Katzev 2008)? While the latter questions will not be of concern in this article, the first rises some interesting issues.

To evaluate the response of the ceramic structure, such as amphorae, a proper material response shall be evaluated. This may be done by selecting and using a proper material model in the modern non-linear finite element software such as LS-Dyna. In general, ceramic model will exhibit linear behaviour up to the fracture point, but using elastic material model with fracture criterion will not provide realistic response. This is because the elastic material model is not able to provide realistic fracture pattern. Due to that, it is not possible to analyse precisely the response of amphorae due to typical handling loads and a more complex material models shall be used, such as Johnson-Holmquist (JH) material models. This material model was developed for studying the response of the ballistic ceramics, that exhibit complex response due to the sudden high-energy impact with e.g. bullet. Although such high-energy event cannot be expected when handling with the amphorae is concerned, it is this material model that is able to realistically represent the post-crack structural behaviour. Determination of JH material models is not straightforward, as demonstrated by e.g. Ruggiero *et al.* (2012).

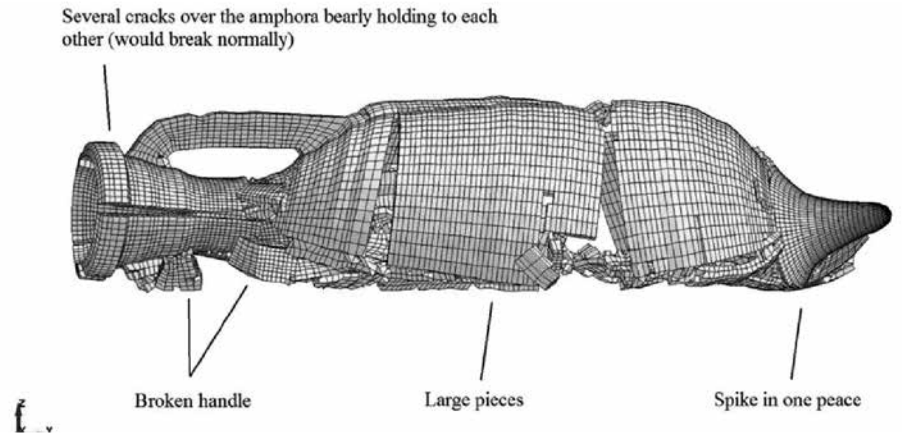

Figure 1 Preliminary structural analysis of ceramic amphorae (Rudan, 2016)

The problem with using the mentioned material model is that it consists of 20 parameters which are not easily obtained. Along with experimental results that are required, additional effort is needed to estimate some of these parameters. Methods for determination of some parameters range from curve fitting methods to Monte-Carlo method fitting.

Within the AdriaS Project preliminary research was performed in that direction, as a prerequisite for any hypothesis testing: only when we have confidence in the application of material model results, some reliable conclusions on amphorae behaviour may be drawn.

3. Wood as a structural material

Until quite recently, wood was the only shipbuilding material used for many millennia of human history, and is still in use. Considering the ancient, but also medieval and post medieval shipbuilders, the wood was used for building ships of every possible size and usage, from the small coastal multipurpose ships to the big warships. Wooden ships are being built without strength calculations, but out of the experience, that was obtained in the 'hard way' – through the real-life tests.

Wooden ships are still built today, but they are often built in a similar old fashion i. e. using skills of skilful designers and builders and not by using, for example, structural analysis for the strength assessment of the wooden structure. This is true not only for "primitive" wooden fishing boats in Africa or Asia, but also for the luxury wooden yachts being built in Northern Europe. The reason for that, among other reasons, is the complexity of the wood as a structural material. In short: wood was once a living organism with complex and organic internal physiology. Due to that reason, structural behaviour of wooden structures is complex and rarely analysed directly. State-of-the-art software, such as LS-Dyna do provide a library with material models used for modelling wooden structures as well, but their application is even more complex than in the case of ceramics: it requires up to 31 material model parameters to properly model the wood structural behaviour. Material model itself was created within a project studying the wooden safety barriers on the roads and the impact of the cars with wooden elements of such barrier. Another application is the analysis of the wooden planks used in construction of the roofs of wooden houses. In both case, some very simple wooden beams are modelled, within a structure far less complex than that of a wooden ship.

An introduction into the application of the material model for wood was performed at Faculty of Mechanical Engineernig and Naval Architecture, University of Zagreb, in the framework of the diploma thesis by Marin Duboković (2015), where experiments and numerical calculations were compared for three types of wood and a three-point bending test. The comparison of results was good but also pointed out the complexity of generation of the models, where only volume finite elements can be used and each element needs to be oriented along the corresponding fibre orientation.

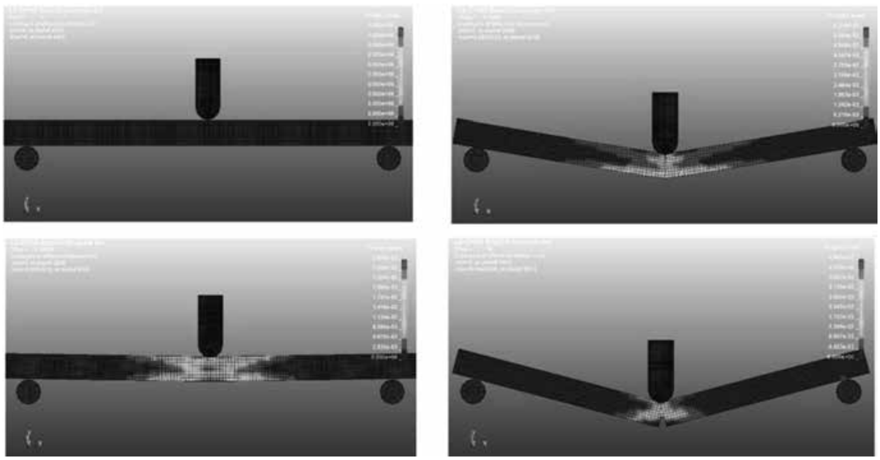

Figure 2 Three-point bending test (Duboković, 2015)

Therefore, there are many interesting and open questions related to the analysis of ancient wooden ships, such as: what is the amount of sagging expected, why certain structural details were changed throughout the history, what amount of the strength reduction may be expected due to ship's keel wearing etc.

4. Sinking ship scenario analysis

As it was already said, shipwrecks are resources of most of the data from the past that are obtained by nautical archaeologists. Depending on what is found at the site, shipwrecks range from the nearly intact ships recently found in depths of Black

Sea (nationalgeographic.com, 2017), to the extremely poor evidence of the wooden hull structure, or just the indirect evidence of the loss of the ship, consisting in ship's equipment and cargo. In the case where the wreck site provides only a limited amount of material evidence, which is the most common case, a logical deduction and reasonable interpretation of the site is required to obtain valuable conclusions.

Sinking of a ship is often a tragic event and many reasons exist for the occurrence of such event: fire on ship, structural failure or flooding due to heavy weather, attack from the enemy ship, and many other reasons. Unusual cargo displacement on the sea bed, such as one recently found near the island of Žirje, where the amphorae are scattered on the rocky slope in the length of about 50 meters (Radić Rossi, Katić 2017), necessitates the analysis of how such event might have happened, and the answer to the question: can we obtain some information about the ship structure by the analysis of the site, where no remains of the ship were found until now?

Recently, the authors performed an attempt to model a sinking event of the ancient ship by using LS-Dyna. A complex non-linear finite element method (NFEM), time domain explicit, fluid-structure interaction (FSI) simulation of such an event is performed. Due to the complexity of the problem a two-stage analysis was set.

In the first part of the analysis a 2D FSI analysis was performed, including contact. The model consisted of the water and air as the primary ambient domains, ship itself and a cargo consisting of 18 independent amphorae. Breaking waves are generated and ship started to move: roll, heave and sway. During the time, additional load is applied to the ship simulating the loss of buoyancy due to water penetration in the hull. Eventually, the buoyancy was reduced enough so that the next wave could sink a ship.

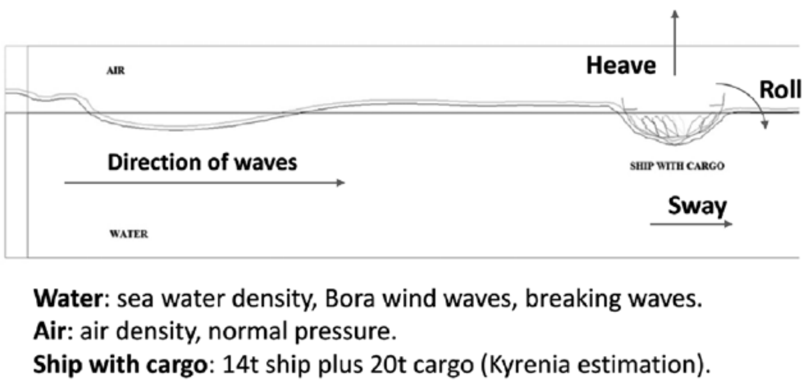

Figure 3 FSI analysis of a Kyrenia class ship with cargo (Rudan and Radić Rossi, 2017).

In the second part of the analysis, a 3D model of ship with cargo was modelled. For the first set of experiments only the hull and 48 amphorae were modelled, although the ship might have carried hundreds of them. Sea bottom was modelled as well. The motions obtained from 2D analysis were applied to the 3D model and once the ship started to sink it was released from any constraints and subjected to sinking. The reduced gravity, acting as a net difference between weight and natural buoyancy of the wood, was applied and a minimal amount of sea current as well. As a result of simulation, ship was sinking until it hit the sea bottom and found its resting place after all the forces went into static equilibrium.

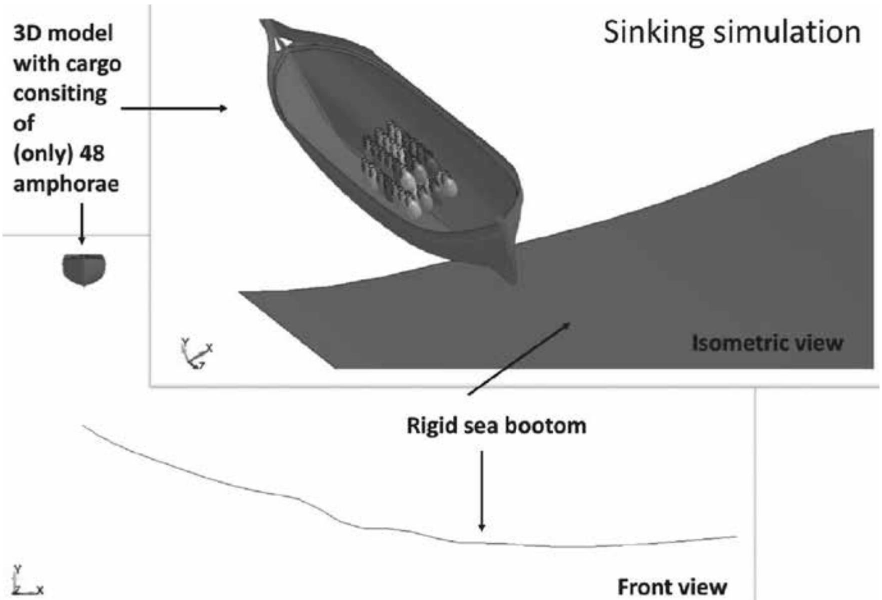

Figure 4 Simulation of ancient cargo ship sinking (Rudan and Radić Rossi, 2017)

Although this two-stage simulation may be further improved, and of increased complexity, it provides the methodology of the study of a ship sinking scenario, which takes into consideration all the most important physical parameters. By variation of any of the parameters of the model, such as ship structure, cargo placement and/or environmental parameters, any hypothesis of how the sinking occurred may be successfully tested. It should be noted that such calculation represents a state-of-the-art analysis which can be successfully applied to contemporary engineering problems such as ship collision, ship accidents forensics and other similar problems.

5. Conclusion

Archaeology of Adriatic Shipbuilding and Seafaring (AdriaS) is a scientific project that aims to introduce the systematic and interdisciplinary research on technological development of shipbuilding and seafaring in the Eastern Adriatic. In a way, it pays respect to ancient shipbuilder and sailors through the analysis of shipwreck sites and gathering of the data on our seafaring ancestors. Since the laws of physics do not change, it is obvious that they were facing similar challenges as we are still concerned with: will the ship be strong and reliable enough, will the cargo survive all the loads, shall the storm be overcame and how etc. In that sense, what archaeology looks on today, once was a living engineering and craftmanship. Therefore, the cooperation between archaeologist and engineers on the presented topic should be considered natural.

Within this paper a brief review of the problems and questions from nautical archaeology was presented from an engineering point of view. Surprisingly, only a limited work was done in that sense, partly because the interdisciplinary approach requires additional effort from all the involved parties, and partly because the analysis of archaeological problems may quickly become very complex, as it was mentioned in the case of the application of ceramics and wood as structural materials. In addition to the inherent complexity of these materials, it should be noted that contemporary software is optimised for researching the modern engineering problems, and is not ideal for the archaeological purpose.

Based on the reported experiments, we can conclude that complex nonlinear analysis, such as fluid-structure interaction and contact including wood and brittle materials, can be successfully applied for testing of various hypothesis that are based on the nautical archaeological evidence.

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Primjena suvremenih inženjerskih metoda u arheologiji broda

Sažetak

Suvremeni interdisciplinarni projekti okupljanju stručnjake iz naizgled nepovezanih područja, poput npr. brodogradnje i arheologije. Ipak, aktualne arheološki nalaze poput antičkih brodova ili keramičke transportne ambalaže nekoć su proizvodili inženjeri i obrtnici. Stoga ima smisla razmotriti funkciju i konstrukciju tih zanimljivih nalaza s inženjerskog stanovišta, s ciljem upotpunjavanja arheološkog istraživanja. Jedna od aktivnosti interdisciplinarnog projekta Arheologija jadranske plovidbe i brodogradnje (AdriaS), koji financijski podržava Hrvatska zaklada za znanost, usmjerena je na razumijevanje strukturnog ponašanja antičkih konstrukcija izrađenih od drva i keramike. Osim toga, metoda povratnog inženjerstva koristi se u analizi podmorskih nalazišta za simulaciju potapanja antičkog broda. U ovome radu predstavit će se mogućnosti i ograničenja suvremenih inženjerskih metoda primijenjenih u arheologiji broda. Pozornost je usmjerena na konstrukcije od drva i keramike, a posebno u dijelu koji se odnosi na identificiranje otvorenih pitanja i primjenu odgovarajućih materijalnih modela. Uz to, prikazana je i složena simulacija potapanja broda metodom interakcije fluida i konstrukcije, kao mogućeg inženjerskog alata za testiranje pretpostavki.

Ključne riječi: nelinearna MKE, interakcije fluida i konstrukcije, antički brodovi, prevrtanje, amfore, arheologija broda