Journal of Experimental Marine Biology and Ecology 374 (2009) 93–103

Contents lists available at ScienceDirect

Journal of Experimental Marine Biology and Ecology

journal homepage: www.elsevier.com/locate/jembe

Mechanics of the right whale mandible: Full scale testing and finite element analysis

Igor Tsukrov [a,*], Judson C. DeCew [b], Kenneth Baldwin [b], Regina Campbell-Malone [c], Michael J. Moore [c]

[a] Department of Mechanical Engineering, University of New Hampshire, Durham, NH 03824, USA
[b] Center for Ocean Engineering, University of New Hampshire, Durham, NH 03824, USA
[c] Woods Hole Oceanographic Institution, Woods Hole, MA 02543,USA

ARTICLE INFO

Article history:
Received 30 April 2008
Received in revised form 16 January 2009
Accepted 10 March 2009

Keywords:
Finite element analysis
Mandible
Mechanical testing
Right whale

ABSTRACT

In an effort to better understand the mechanics of ship-whale collision and to reduce the associated mortality of the critically endangered North Atlantic right whale, a comprehensive biomechanical study has been conducted by the Woods Hole Oceanographic Institution and the University of New Hampshire. The goal of the study is to develop a numerical modeling tool to predict the forces and stresses during impact and thereby the resulting mortality risk to whales from ship strikes.

Based on post-mortem examinations, jaw fracture was chosen as a fatal endpoint for the whales hit by a vessel. In this paper we investigate the overall mechanical behavior of a right whale mandible under transverse loading and develop a finite element analysis model of the bone. The equivalent elastic modulus of the cortical component of right whale mandible is found by comparing full-scale bending tests with the results of numerical modeling. The finite element model of the mandible can be used in conjunction with a vessel-whale collision event model to predict bone fracture for various ship strike scenarios.

1. Introduction

The North Atlantic right whale, *Eubalaena glacialis*, is one of the most critically endangered whales in the world (International Whaling Commission, 2001). Anthropogenic mortality, including deaths resulting from vessel-whale collisions and entanglement in fishing gear, accounted for 27 (64.3%) of the 42 right whales examined postmortem between 1970 and January 2008 (Campbell-Malone et al., 2008; Moore et al., 2005). Of the 21 vessel-related deaths examined postmortem, 11 (52.4%) resulted from sharp (propeller) trauma, and 9 (42.9%) resulted from blunt contact with the hull of a vessel. (In one additional case, the vessel-whale collision was reported anecdotally but when the carcass was examined no trauma mechanism could be determined based on the observed injuries.) A thorough review of available necropsy reports for right whales examined between 1970 and Dec 2006 revealed common injuries seen in right whales killed by vessels. These included hemorrhage, broken bones (i. e. skulls, jaws and vertebrae) and disarticulated ribs (Campbell-Malone et al., 2008). Vessel-whale collisions are being extensively studied using various approaches including historical data processing and hydrodynamic analysis (Knowlton et al., 1998; Laist et al., 2001; Vanderlaan and Taggart, 2007; Jensen and Silber, 2003).

The U.S. government recently enacted speed restrictions for vessels traveling through right whale critical habitat in an effort to reduce the likelihood of fatal collisions (National Marine Fisheries Service (NMFS)- National Oceanic and Atmospheric Administration (NOAA), 2008). These restrictions will expire in five years unless they are found to be effective at reducing vessel-related mortality and are thereby reauthorized.

The ultimate goal of an on-going collaborative project conducted by the Woods Hole Oceanographic Institution (WHOI) and the University of New Hampshire (UNH) is to evaluate the efficacy of speed restrictions in terms of reducing the force of impact and thereby mortality due to blunt ship strikes. This is done via the creation of a finite element analysis (FEA) model to predict damage to whale skeletal components produced by various collision scenarios. The biomechanical modeling effort involves several components which are investigated separately and then combined to quantify the mechanics of interaction between a whale and a vessel during collision. In particular, one has to decide what kind of trauma should be considered as critical for a whale, evaluate the intensity of forces sufficient to cause the observed trauma, and determine whether such forces are produced for a given collision scenario (vessel size and approach speed, hull geometry, relative positions of whale and vessel prior to impact).

A previous study identified mandibular fracture as a viable fatal endpoint upon which a ship strike model could be based for several reasons (Campbell-Malone, 2007). Firstly, a fractured mandible has been found in 33% of blunt ship-strike cases examined postmortem since 1970. Secondly, with appropriate failure criteria, bone fracture can be modeled as a binary condition (i.e. failure, no failure). In addition, no fully healed jaw fractures have been found to date in right whales, making mandibular fracture a reasonable proxy for fatality. The simple geometry of this bone lends itself well to modeling. Also, the right whale mandible has relatively thin soft tissue protection (on

---

[*] Corresponding author. Tel.: +1 603 862 2086; fax: +1 603 862 1865.
E-mail address: igor.tsukrov@unh.edu (I. Tsukrov).

0022-0981/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jembe.2009.03.012

the order of 20 cm total, whereas 20 cm of a highly compliant blubber layer along with an even thicker layer of skeletal muscle cover the rest of the skeletal elements). Finally, the length of the mandible of large whales, measuring 25–30% of the total body length, represents one of the longest single bones in any extant group and is a relatively large target in the vessel-whale collision (Campbell-Malone, 2007).

In this paper we investigate the overall mechanical behavior of a right whale mandible under transverse loading and develop a finite element analysis model of the bone. By combining full-scale mechanical experiments on the intact bone with numerical simulations, we determine the effective elastic modulus of cortical bone which is needed to calculate strains and stresses in the mandible during a collision event. The information on strain and stress concentrations can then be used with the corresponding bone fracture criterion (see, for example, Doblare et al., 2004) to predict damage imparted on the whale due to ship strike. The numerical model of the overall collision event is presented in (Raymond, 2007); the experimental program to determine local elastic stiffness and breaking strength of trabecular and cortical components of the right whale mandible is described in (Campbell-Malone, 2007; Campbell-Malone et al., in preparation).

This paper is organized as follows. Section 2 describes the mandible analyzed in this study (Fig. 1). The full-scale experiment conducted to evaluate mechanical behavior of the bone under transverse loading is described in Section 3. Section 4 focuses on the development of a finite element model of the mandible. In Section 5, the FEA model is used in conjunction with the experimental results to determine the equivalent mechanical properties of the cortical bone needed for the collision event model. Section 6 contains discussion of the results and establishes correlation of this work to the concurrent research efforts that include more detailed understanding of mechanical and physical properties of the right whale mandible tissue on the millimeter scale, as well as a related FEA effort to model the entire vessel-whale collision event.

2. Right whale mandible analyzed in this study

Individual right whales can be identified based on patterns of thickened skin patches found naturally on their heads and other unique markings. The New England Aquarium maintains a photo-identification catalog and sighting record for identified individuals who are each assigned an ID number (Right Whale Consortium, 2007). This number begins with Eg (the initials of the scientific name for right whales, *Eubalaena glacialis*) followed by a 4-digit number. The mandible analyzed in this study was taken from right whale Eg# 1004, a mature female right whale that died as a result of a vessel-whale collision. The animal measured 16.0 m (52.49 ft) in total length and was at least 29 years old, according to the sighting record (Right Whale Consortium, 2007). At the time of necropsy, the robust blubber coat and excellent skin condition indicated that the animal was in very good health prior to death and lacked obvious signs of chronic illness or starvation. Eg# 1004 had also successfully reproduced at least five times and was pregnant with her sixth known offspring at the time of death.

Fig. 1. 3-D laser scanning of the mandible at the Woods Hole Oceanographic Institution (MA, USA) to determine the surface geometry.

After a necropsy was performed on the animal, the left and right halves of the mandible were retrieved and were frozen within days of the necropsy. These bones represent the freshest right whale jaw bones available for study, with no appreciable loss of water or oil prior to sample preparation. The mandibles were wrapped in thick plastic sheeting and were kept at −20 °C (−4 °F). The right half of the mandible was selected for full-scale testing and numerical modeling (Fig. 1). The plastic sheeting was removed and the bone was wrapped several times over in thin clear plastic wrap and was stored below room temperature for one week during full-scale mechanical testing. During this time it was estimated that less than 4 oz of fluid seeped from the entire bone. The bone was then re-wrapped in the plastic sheeting and was refrozen. The tested mandible was 399.5 cm (13.11 ft) straight length and 449.5 cm (14.75 ft) external curved length. It weighed 224 kg (493.8 lb).

3. Full-scale mechanical testing

The purpose of the full-scale testing was to evaluate the overall stiffness of the mandible when subjected to bending by transverse loading. The bone was loaded quasi-statically by a point force applied in the middle while two ends were simply supported. The strains and displacements in the designated locations were recorded for values of force varying from 0 to 4448 N (1000 lbf). These data can be used to determine the equivalent mechanical properties of the bone material, to validate predictions obtained using numerical simulations or simplified strength-of-material models, and to quantify deformation of the mandible during ship strike.

3.1. Experimental set-up

The choice of the experimental set-up was defined by three concerns. First, the loading and boundary conditions must provide deformation as close to pure bending as possible. This condition is not easily satisfied due to irregular cross-section of the bone and a complicated geometry of its ends. Secondly, the coordinate system must be clearly defined so that the experimental results could be compared with the numerical modeling predictions. And thirdly, the strain gage placement on the bone must be chosen to provide meaningful information on strain components during loading.

3.1.1. Loading and boundary conditions

Due to the irregular cross-section of the bone and its inherent curvature it was decided that the best way to produce pure bending deformation was to suspend the bone from a gantry crane and load it by suspending weights (see Fig. 2a). The bone was supported by two one-inch spectra straps on the left and right ends, and the weights were hung by two one-inch spectra strapping at the mid-point of the bone. This configuration provided the so-called "simple support" conditions free from the complications associated with constraining moments. This enabled greater ease when comparing the experimental tests on the bone to the numerical simulations as all the forces were in a single plane.

3.1.2. Coordinate system

A precise coordinate system was needed to relate the strains and deflections of the mandible to the finite element model. The longitudinal surface of the bone was denoted as the *X*–*Z* plane,