Available online at www.sciencedirect.com
ScienceDirect
Ocean Engineering 34 (2007) 206–217
OCEAN ENGINEERING
www.elsevier.com/locate/oceaneng

Technical note

Structural modeling and testing of a concrete canoe

F. Paradis[a,*], G. Gendron[b]

[a]CRIB-Department of Civil Engineering Université Laval, Ste-Foy, Canada G1 K 7P4
[b]GIREF-Departement of Mechanical Engineering, Université Laval, Ste-Foy, Canada G1 K 7P4

Received 7 August 2005; accepted 11 January 2006
Available online 19 April 2006

Abstract

A finite element model is set up and experimental tests are performed to help understand the behavior of a concrete canoe and subsequently optimize its design. First, the performance criteria that must be satisfied to participate at the annual ASCE/Master Builders competition are described. Then, the finite element model and the different loading cases that were studied are presented. Results from these loading cases are discussed and used to optimize the material properties as well as the thickness of the hull and the dimensions of the gunwale and reinforcing ribs. Static and dynamic experimental tests were also conducted to validate the results of the finite element analyses. The results indicate that the main stresses and strains are caused by the static load cases. The additional stresses caused during races are small.

Keywords: Canoe; Lightweight concrete; Design criteria; Finite element model; Laminate design; Experimental measurements

1. Introduction

Since 1988, Degussa Admixtures (Master Builders Technologies) has sponsored an annual civil engineering competition which involve undergraduate students who are challenged to design a concrete laminate and use it to build an aesthetic canoe that will display good performances in races. In the USA, there are 18 regional competitions and each winner is then invited to a national competition. The winning team from Canada is also invited at the national US competition as an international entry. Along with participating to canoe races, each team must also prepare a technical information display, as well as an oral presentation. The canoe is evaluated before and after the races for durability. Each team must finally produce a report explaining how they developed the concrete-based laminate, designed the canoe, and built it.

The 2002 National Concrete Canoe Competition (NCCC) main rules (NCCC, 2002) are:

1. The canoe must be designed and constructed by engineering students during the current year.
2. The canoe must float horizontally when filled with water;
3. Reinforcement material can be used as long as it satisfies the Ottawa sand test which specifies that one cup of material passes through a 4″ diameter cylinder in less than 10 s.
4. The total thickness of the reinforcement materials should not exceed 50% of the hull thickness.
5. The hull can be stiffened using ribs and gunwale as long as the total thickness of the reinforced hull does not exceed four times the thickness of the unreinforced wall.

The objective of this work is to improve the understanding of the structural behavior of a concrete canoe and present a few design criteria. To reach this goal, a finite element model was established and validated by in situ tests. Dynamic experimental tests were also performed to evaluate the amplification factor that should be applied to the static stress to take dynamic effects into account. Laval University's "*Apogee 2002*" concrete canoe was chosen for the in situ tests (see Fig. 1). It was found that the design criteria established during the course of this work definitely helped optimize the mass of the 2003 and 2004 canoes.

*Corresponding author. Tel.: +1 418 656 2131; fax: +1 418 656 3355.
E-mail address: Francois.paradis@gci.ulaval.ca (F. Paradis).

0029-8018/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.oceaneng.2006.01.006

Fig. 1. *Apogee 2002* concrete canoe and team members.

2. Canoe and composite description

Modeling using finite element analyses requires knowledge on the composites' mechanical properties as well as the canoe's geometry. The property characterization of the composites is crucial. The 2002 *Apogee* team deployed tremendous efforts in developing the final composites. See Paradis (2004) and Paradis and Jolin (2004) for a detailed description of these efforts. The presented conclusions reveal, amongst other things, that the studied composite can be considered isotropic and linearly elastic. The measured mechanical and physical properties have also been reported in the two above-mentioned references. They are presented in Table 1.

Table 1
Laminate's material properties

Property	Hull and gunwale	Ribs
Young modulus (MPa)	5000	6100
Poisson ratio	0.28	0.28
Density (kg/m^3)	670	755
Thickness (mm)	7	11×18
Tensile strength (MPa)	4.7	6.7

The concrete canoe's shape follows the plans presented in Fig. 2. The canoe weighs 35 kg and is 6.4 m long. Its largest section is 672 mm wide and the canoe is 291 mm deep. Slight rockers of 60 mm are provided both at the bow and stern to ease racing maneuvers. The 7 mm hull is reinforced by four ribs that are 11 mm high and 18 mm wide. Ribs are 800 mm apart and made of a stiffer and stronger laminate than the hull (see Table 1). As indicated in Fig. 2, ribs are numbered 1–4. More attention will be paid to rib #4 in the analysis of the results as it is the most stressed. A 7 mm thick and 28 mm wide gunwale stiffens the upper part of the hull over the entire length of the canoe.

The construction of the canoe began by hand filling all four ribs with concrete and placing within them the reinforcing carbon scheme: three rows of six carbon yarns. The ribs are constructed by alternatively placing a layer of concrete and a layer of carbon yarns. This operation is repeated three times. Then, the transversal carbon yarns are placed. Each rib is secured to the hull with seven transversal carbon yarns located along the length of each rib. Immediately after the construction of the ribs, the construction of the hull followed the cross-sectional layout presented in section B-B of Fig. 2. The hull construction started with a first layer of fiberglass [0/90] mesh placed over the male mold and impregnated with concrete. Then, successive layers of carbon [0/90] meshes were placed, each layer manually impregnated with concrete. After placing the fourth layer of carbon mesh, the exterior fiberglass mesh was added and covered with a final coat of concrete. To prevent the concrete from drying during construction, the relative humidity in the construction laboratory was kept at 100%. Following construction, the canoe cured for 28 days under wet burlaps. While curing, the outer surface of the hull was sanded and corrected with the concrete mix used for construction. After removing the mold, minor imperfections were similarly corrected on the gunwales, ribs and inner surface. Finally, the canoe was primed and painted on most of its surface. Only a small section was left unpainted to comply with the rules (see Fig. 1). The entire canoe was then clear coated and waxed to a mirror perfect finish.

3. Finite element model

The canoe's performance strongly depends on its design. An excellent laminate construction as well as an optimal placement of stiffening ribs and gunwale also improve