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Shell strength and fishing damage to the smooth clam (*Callista chione*): simulating impacts caused by bivalve dredging

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The smooth clam *Callista chione* is exploited by a fleet of dredgers along the southwestern coast of Portugal and suffers from a high incidence of shell damage. The force required to break *C. chione* shells in relation to fishing impacts and dredge damage is quantified. Fishing trials and shell-strength measurements (compression and compaction experiments) were performed to determine whether shell damage was attributable to the direct impact of the dredge teeth or to sediment compaction. A three-dimensional model of *C. chione* was subjected to simulated force by the finite element method. Analyses of damage areas and breakage patterns revealed two groups of samples, one containing the samples from compression experiments and another with the samples from dredging and compaction experiments, suggesting that most shell damage was attributable to compaction within the sediment. Information is provided to help improve the design of bivalve dredges, by increasing both length and angle of the dredge teeth, which would reduce the compaction force and distribute it differentially within the sediment, forcing upward movement of the bivalves.

Keywords: bivalve dredging, *Callista chione*, dredge design, fishing damage, shell strength, smooth clam.

Introduction

In the past two decades, several studies have been carried out to assess the impact of mechanical and hydraulic dredges on bycatch and macrobenthic communities (see review by Gaspar and Chícharo, 2007), but few have addressed mitigation of the damage inflicted by these gears on the target species. The issue of shell damage caused by fishing has long been recognized as a problem, and one area of particular concern is the damage and subsequent mortality caused to discards in mechanized bivalve fisheries. Several authors (e.g. Gaspar *et al.*, 1998; Moschino *et al.*, 2003) reported that a significant proportion of target species caught or left on the dredge path have damaged shells (with chipped margins, holed umbos, broken or smashed valves), which cause indirect fishing mortality and exert economic loss. Nevertheless, not all individuals with damaged shells die. Although bivalves have the ability to repair their shells (Robinson and Richardson, 1998; Ramsay *et al.*, 2000; Schejter and Bremec, 2007), the energetic costs of this process are considerable, reducing the energy available for growth and reproduction (Palmer, 1992).

Shell strength can be measured by quantifying the maximum force required to break the shell (LaBarbera and Merz, 1992; Roy *et al.*, 1994). Several studies on molluscan shell strength have been published, including specific work on techniques and instrumentation for shell-strength measurements (Garden, 1998). Studies on shell strength have different purposes to estimate species vulnerability to parasitic, symbiotic, endobiont, or epibiont infestations (Dunphy and Wells, 2001; Stefaniak *et al.*, 2005; Buschbaum *et al.*, 2007), the risk of predation by crustaceans, fish, and birds (Blundon and Kennedy, 1982; Preston *et al.*, 1996; Brodersen and Madsen, 2003), and the effect of shell repair on shell strength (Blundon and Vermeij, 1983). Other workers have analysed interspecific (Cabral and Natal Jorge, 2007) or intraspecific variations in shell strength according to different environmental conditions (Lewis and Magnuson, 1999; Nagarajan *et al.*, 2006), pollution effect on shell strength (Jordaens *et al.*, 2006), and implications of shell strength for aquaculture purposes (Beadman *et al.*, 2003; Grefsrud and Strand, 2006). Specifically related to bivalve fisheries, some studies have estimated shell damage and the susceptibility to shell breakage when exposed to different types of fishing operation, duration, and gear characteristics (Tuck *et al.*, 2000; Gaspar *et al.*, 2002; Leitão *et al.*, 2009). Other studies have assessed the sensitivity of bivalves to breakage by harvesting and sorting equipment (Coffen-Smout, 1998) or aimed to improve the design of handling systems (Garden, 1998).

The smooth clam *Callista chione* is an Atlantic–Mediterranean warm-temperate species, which is commercially exploited in Portugal (Gaspar *et al.*, 2001), Spain (Tirado *et al.*, 2002), France (Charles *et al.*, 1999), Italy (Valli *et al.*, 1983–1984), and Greece (Metaxatos, 2004). In Portugal, it is more abundant on the southwest coast, where it is exploited by a fleet of 24 dredgers. Owing to the increasing commercial importance of the fishery for smooth clams in Portugal, some work has been performed recently on the dredge impact on benthic communities, selectivity, and bycatch (Gaspar *et al.*,

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2001) and on *C. chione* biology (Moura *et al.*, 2008, 2009). During those studies, some 20% of the clams caught had shell damage, prompting efforts to minimize the problem. With this purpose, experiments were conducted to quantify the force required to break *C. chione* shells, which are subject to physical impact and damage inflicted during the dredging operation. The study also aimed to gather the information necessary to improve the technical design of the dredge, to reduce bivalve shell damage and consequently to minimize indirect fishing mortality, on clams of both commercial size and undersized discards.

Material and methods

Samples of smooth clam were dredged by IPIMAR's RV "*Donax*" from a site off Arrábida (southwest Portugal; Figure 1). They were taken on sandy seabed ~10–12 m deep. Tows were performed parallel to the shore, at a towing speed of 1–2 knots and duration ~15 min. The fishing gear was similar to the dredges used by the commercial fleet. The dredge weighs ~90 kg and consists of a metallic frame, a toothed lower bar, and a rectangular metallic grid box opening posteriorly (for further detail on dredge design, size, and characteristics, see Gaspar *et al.*, 2001).

Experimental fishing trials were carried out to determine whether the damage inflicted on the bivalves was attributable to (i) direct impact of the teeth of the dredge on the shells, or (ii) compaction of the shells within the sediment exerted by the toothed bar of the dredge. During the fishing trials, scuba divers followed the dredge and collected the commercially undersize clams (<60 mm shell length, SL) that were dislodged from the sediment, passed through the metallic grid box, and remained exposed on the dredge path. Damaged clams were analysed to assess the damage inflicted by dredging, and undamaged clams were kept for subsequent use in shell-strength experiments.

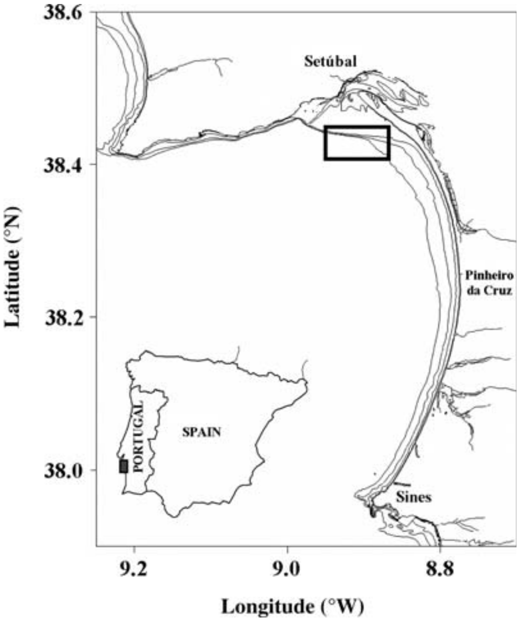

Figure 1. Location of the Setúbal region (southwestern Portugal) with the *C. chione* sampling area shown as a rectangle.

Shell morphometrics

Shell strength is expected to be size-dependent, so morphometric parameters of individual clams were measured to detect eventual correlations with the force required to break the shells (namely SL, the maximum distance along the anterior–posterior axis), shell height (SH, the maximum distance along the dorso-ventral axis across the mid-axis of the shell), shell width (SW, the maximum distance along the lateral axis between the two valves of the closed shell), and shell thickness (ST) in the broken section. The measurements of SL, SH, and SW were made with a digital calliper (precision 0.01 mm) and the measurement of ST in the broken sections with an analog micrometer. Individual clams were weighed (total weight, Tw; shell weight, Sw) on a top-loading digital balance (precision 0.01 g).

To estimate the internal volume of the shell (Sv), both valves were completely filled with water, and the total volume transferred into a tared recipient vessel and weighed on a top-loading digital balance. An earlier test, in which the water contained within the two valves was transferred into a graduated glass container, weighed, and compared with the volume, confirmed the accuracy of this means of estimation. The revised method allowed the water to be weighed rather than the more time-consuming method of direct volume determination, using the direct conversion formula weight $(g) = \text{volume } (\text{cm}^3)$.

Measurements of shell strength

Continuous loading experiments were conducted to estimate the force needed to break *C. chione* shells. The shell-failure load (the maximum load sustained by the shells) theoretically approximates the force required to damage individuals during dredging. Shell strength was measured using an automatic force gauge (SEIDNER® Form + Tester), previously tested for its suitability, rigour, and precision in shell-compression experiments. The force was applied continuously and without shock on the bivalve shell surface. The downward movement of the cross-head was kept constant at $500\ \text{N}\ 15\ \text{s}^{-1}$ $(\text{N} = \text{kg m s}^{-1})$ during all experiments. When the measuring instrument detected that the shell was starting to crack, the force was removed. Failure load at the striking point was measured at the moment of shell collapse (i.e. the force required to break the shell), and all loading forces were measured in Newton (N).

The natural position of *C. chione* in the seabed is burrowed dorso-ventrally into the sediment (with the ventral margin upward-facing towards the sediment–water interface). Assuming that dredge teeth might touch the bivalves during fishing operations, we assume that contact would take place on the highest point of the shell. Therefore, to reproduce fishing conditions in our experiments, we measured shell strength in whole bivalves (without the soft contents) and applying the load vertically at the point of maximum shell convexity (the mid-lateral surface of the shell), invariably on the right valve. As those shells had been dried at room temperature (for measurement and weighing), they were well-wetted immediately before testing, to return them to their natural condition, a procedure that is unlikely to affect shell strength (Currey, 1979).

Before measuring shell strength, the clams were carefully inspected and some were discarded as a consequence of having already sustained slight damage to the shells, e.g. small fractures, broken or dislodged umbos, drilling attempts, evidence of shell repair, and other scars. The whole set of experimental clam

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shells was then subdivided into two groups of similar length frequency distribution, which were to be subjected to different types of shell-strength measurement:

(i) compression (point-load) experiments, designed to reproduce a direct impact of dredge teeth on the surface of the shell (Figure 2a). Compression was applied directly to the bivalve surface, the shells being held in place with a small piece of plasticine, to avoid movement during load measurements (Figure 2b);

(ii) compaction experiments, designed to simulate progressive pressure on the shell within the sediment, as exerted by the toothed bar of the dredge (Figure 2c). The compactional load was applied onto a metallic recipient filled with fine wet sand (collected during the fishing trials) in which the shells were embedded (Figure 2d).

The terms used throughout this study (compression vs. compaction and compressive vs. compactional) follow the terminology adopted by Zuschin and Stanton (2001) to distinguish between experiments using a locally concentrated force (compression experiments: a point-load to assess the punching resistance of the shells to the impact from the dredge teeth) or an evenly distributed force (compaction experiments: a uniform load to assess the plane axial and shear resistance of the shells to deformation within the sediment).

Damage areas and breakage patterns

To describe the damage inflicted to the shells and compare the damaged areas and breakage patterns caused by dredge impact (dredge sample) and the two experimental simulations (compression and compaction samples), the two valves of each clam were subdivided for description into four areas according to the

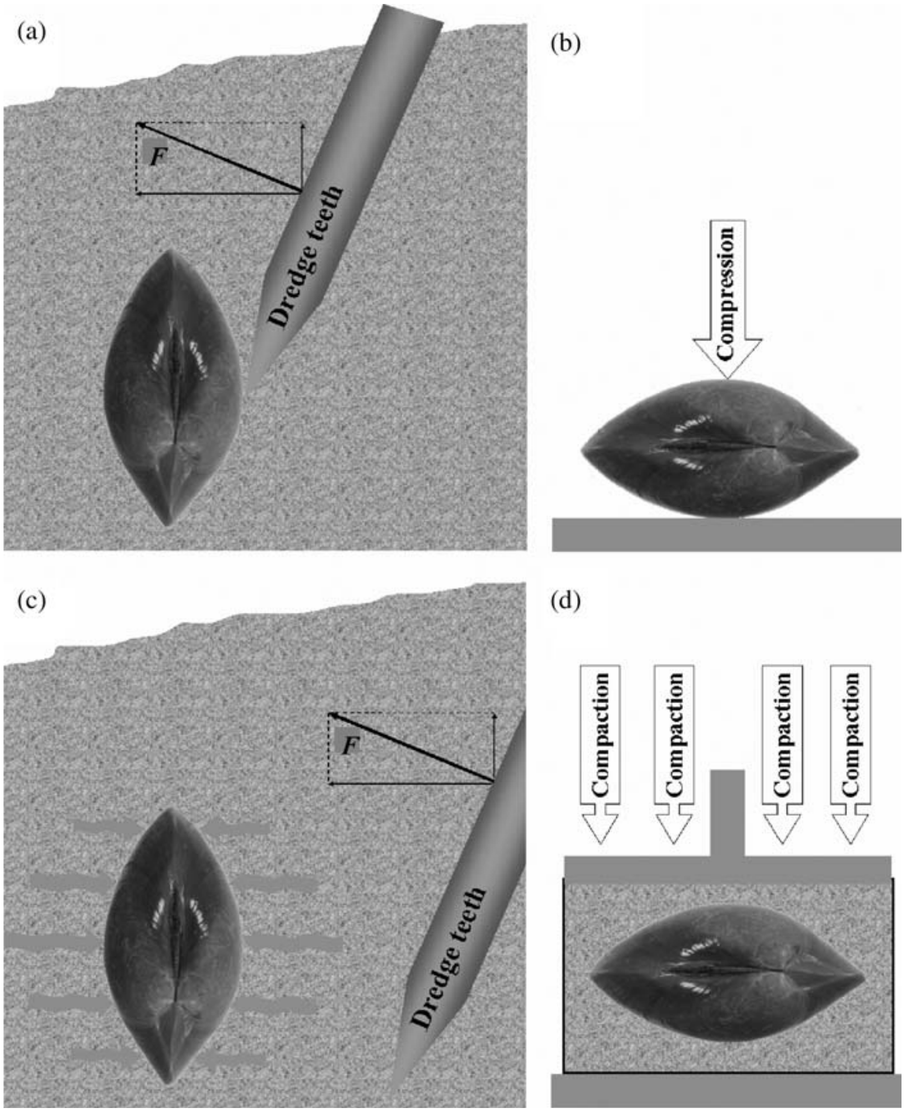

Figure 2. Illustration of *C. chione* burrowing position in the substratum, forces exerted at the passage of the dredge through the seabed, and shell-strength measurements: (a) compressive force on the shells attributable to the direct impact of the dredge teeth; (b) compression experiments; (c) compactional force on the shells attributable to the progressive pressure within the sediment exerted by the toothed bar of the dredge; (d) compaction experiments.

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shell's main axes (Figure 3a), anterior dorsal (AD), posterior dorsal (PD), anterior ventral (AV), and posterior ventral (PV). Immediately after the fishing trials and measurements of shell strength, the position of the main areas of shell damage was assigned to one or more of these four areas. Subsequently, the frequency distribution of each damaged area (AD, PD, AV, and PV) detected in each shell (right and left valves from the dredge, compression, and compaction samples) was calculated and represented graphically according to the following damage scores: 1, damage $\leq$ 25%; 2, 25% $<$ damage $\leq$ 50%; 3, 50% $<$ damage $\leq$ 75%; 4, damage $>$ 75%.

Three-dimensional model of the shell and simulations using the finite element method

To simulate breakage/fracture of the bivalve shell, a simplified replica of a *C. chione* shell was computerized using morphometric data from 15 animals, each from a different size class sampled during the study (5-mm size classes, ranging from 25–30 to 95–100 mm SL). For the purpose, besides the linear measurements described above (SL, SH, and SW), additional measurements of ST were made with an analogical micrometer, and arc and perimeter measurements were made with a digital imaging system (Zeiss® KS100, release 3.0), aiming to characterize the bivalve's volume and shape (Figure 3b).

The assemblage of morphometric parameters was graphically transformed into a three-dimensional model of *C. chione*, developed using the software AutoCAD© (Figure 3c). The three-dimensional model of the shell was constructed using triangular elements with six nodes. Overall, it contained a total of 292 finite elements and 641 nodes, and the Poisson coefficient was 0.17. Subsequently, the three-dimensional model was subjected to simulated forces through the finite element method (FEM), using the software Robot Millennium©, v. 15.1. The FEM provides detailed visualization of where structures bend or twist, indicating the distribution of stresses and displacements, so was used to assess the major areas of tension and traction in both experiments (compressive and compactional loadings).

In the numerical simulations based on the FEM, the object is subdivided into a set of small discrete regions, the finite elements, linked by common points, the nodes (Zienkiewicz and Taylor, 2005). The mechanical behaviour of each element is analysed in terms of the loads and responses at the nodes and is described by an elemental matrix, relating a vector nodal displacement to a vector of applied nodal forces. The matrices of all elements are combined into a large matrix representing the whole complex system, which is then transformed into a set of simultaneous equations, which is solved for unknown values using the techniques of linear algebra or non-linear numerical schemes.

Data analysis

The size ranges (SL) of the three samples of *C. chione* (dredge, compression, and compaction experiments) and the forces required to break the shells in the two shell-strength measurements (compressive and compaction experiments) were compared with one-way analysis of variance (ANOVA). Whenever ANOVA assumptions (normality of data and homogeneity of variances) were not met, a Kruskal–Wallis (K–W) test (ANOVA on ranks) was performed. A Pearson product-moment correlation analysis was carried out to evaluate the correlations between morphometric variables and the forces in both shell-strength measurements (compression and compaction experiments). The number of damaged valves was compared between samples of *C. chione* (dredge, compression, and compaction experiments) through a Chi-squared test. Statistical analyses were performed using the

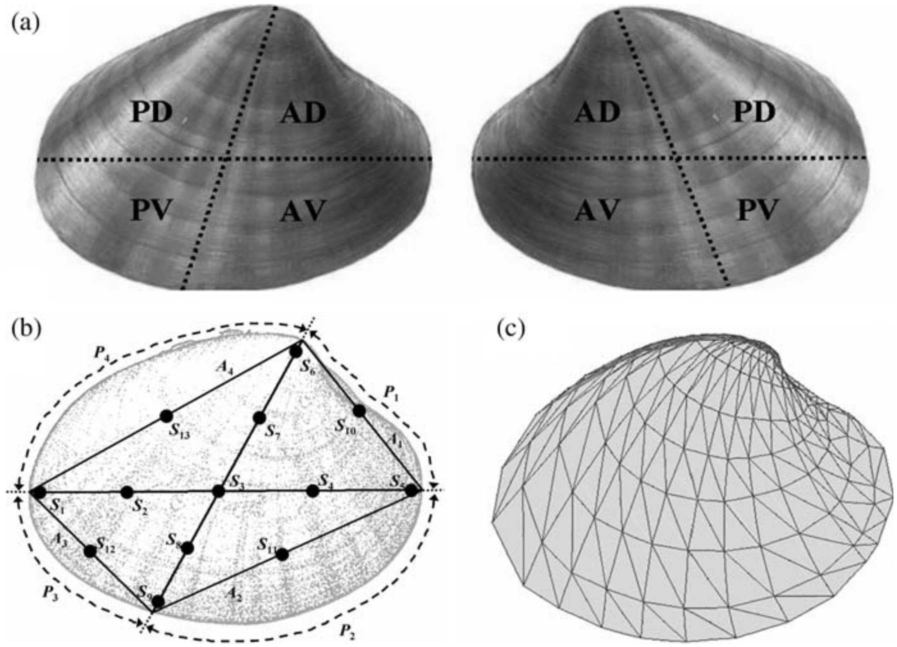

Figure 3. (a) Subdivision of the shells for detection of damage areas and patterns (AD, anterior dorsal; PD, posterior dorsal; AV, anterior ventral; PV, posterior ventral); (b) schematic representation of the shell parameters measured to create the three-dimensional model of *C. chione*. S_n, shell points with linear measurements (SL, SH, SW, and ST); A_n, arc measurements; P_n, perimeter measurements; (c) three-dimensional model of the shell of *C. chione* subjected to simulated forces through the FEM.

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software package SigmaStat© v3.5, with significance determined at $p < 0.05$.

Results

Shell morphometrics

The sample of *C. chione* damaged by dredging operations consisted of a total of 134 individuals, with a mean size of 62.81 ± 16.69 mm SL (range: 25.00 − 97.00 mm SL). For the compression and compaction experiments, undamaged bivalves were divided into two homogeneous sets with wide size ranges, and 116 bivalves were subjected to point-load experiments (range: 26.31 − 98.45 mm SL) and 122 were used for compaction experiments (range: 27.77 − 98.36 mm SL; Table 1). SL was not significantly different between the three samples (dredge, compression, and compaction experiments; K–W: $H = 5.113$, $p = 0.078$), so the bivalves we used for measuring shell strength were deemed comparable and reflecting the broad size range of individual clams damaged during dredging.

Shell strength

The forces sustained by *C. chione* shells were markedly distinct between shell-strength measurements (K–W: $H = 176.24$, $p < 0.001$), being lower in compression experiments (580 ± 318 N, range: 39 − 1743 N) than in compaction experiments (3265 ± 1046 N; range: 1068 − 5831 N; Table 1). Given the broad size range of the shells subjected to strength measurements (with the consequent high inter-individual variability in shell strength), data are also reported in terms of force as a function of SL (Figure 4).

The relationships established between morphometric parameters and the shell strength of *C. chione* subjected to compression and compaction experiments are listed in Table 1. As expected, all relationships were statistically significant and confirmed that shell morphological variables were highly correlated and linearly dependent. The correlation coefficients were invariably higher in compression experiments ($r = 0.382$, $p < 0.001$ to $r = 0.468$, $p < 0.001$) than in compaction experiments ($r = -0.214$, $p < 0.05$ to $r = -0.321$, $p < 0.001$). The correlations were consistently positive in compression experiments and negative in compaction experiments, i.e. the forces required to break *C. chione* shells increased with clam size in point-load tests and decreased with clam size in compaction tests. The best predictors of shell strength were ST in compression experiments ($r = 0.468$, $p < 0.001$) and Sw in compaction experiments ($r = -0.321$, $p < 0.001$).

Damage areas and breakage patterns

The sample of *C. chione* damaged during bivalve dredging ($n = 134$) provided a total of 153 damaged valves (19 clams had both valves damaged). Right valves were more frequently damaged (53.6%) than left (46.4%). The compression experiments ($n = 116$) induced damage in 157 valves (41 clams had both valves broken), with a dominance of right valves (54.8%) over left (45.2%). The compaction experiments ($n = 122$) damaged a total of 166 valves (44 clams had both valves damaged), with left valves more frequently damaged (58.4%) than right (41.6%). Only in compaction experiments were statistically significant differences detected in the number of right and left valves damaged ($\chi^2 = 4.39$, $p < 0.05$).

Table 1. Descriptive statistics (number, mean ± s.d., and range) and matrix of the Pearson product–moment correlations established between morphometric parameters and shell strength (force) of *C. chione* subjected to compression (above diagonal) and compaction (below diagonal) experiments.

	Compression experiments ($n = 116$)							
Compaction experiments ($n = 122$)	**SL (mm) [66.69 ± 19.45 (26.31–98.45)]**	**SH (mm) [56.07 ± 17.36 (20.77–85.01)]**	**SW (mm) [30.80 ± 9.66 (10.17–44.85)]**	**ST (mm) [2.40 ± 0.71 (0.64–4.26)]**	**Tw (g) [71.83 ± 47.61 (3.00–177.50)]**	**Sw (g) [46.08 ± 29.79 (2.30–108.10)]**	**Sv (cm^3) [50.80 ± 32.96 (3.34–128.62)]**	**Force (N) [580 ± 318 (39–1 743)]**
SL (mm) [65.74 ± 19.64 (27.77–98.36)]	–	0.996***	0.993***	0.871***	0.957***	0.957***	0.970***	0.425***
SH (mm) [55.39 ± 17.52 (22.07–82.39)]	0.997***	–	0.994***	0.875***	0.958***	0.959***	0.969***	0.416***
SW (mm) [30.52 ± 10.11 (12.09–48.97)]	0.991***	0.992***	–	0.892***	0.960***	0.962***	0.966***	0.431***
ST (mm) [2.45 ± 0.87 (1.04–5.15)]	0.841***	0.849***	0.875***	–	0.859***	0.881***	0.818***	0.468***
Tw (g) [71.37 ± 50.42 (4.70–196.40)]	0.945***	0.948***	0.963***	0.898***	–	0.995***	0.982***	0.416***
Sw (g) [46.06 ± 32.08 (3.30–126.20)]	0.940***	0.945***	0.961***	0.914***	0.996***	–	0.978***	0.426***
Sv (cm^3) [49.87 ± 33.46 (1.94–124.64)]	0.969***	0.969***	0.973***	0.830***	0.977***	0.969***	–	0.382***
Force (N) [3 265 ± 1 046 (1 068–5 831)]	−0.215*	−0.214*	−0.232**	−0.220*	−0.320***	−0.321***	−0.284**	–

*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

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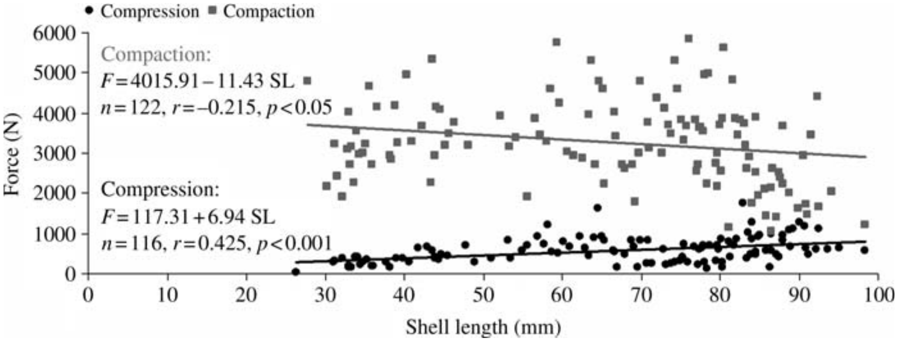

Figure 4. Force (shell strength) as a function of *C. chione* size (SL) in compression and compaction experiments.

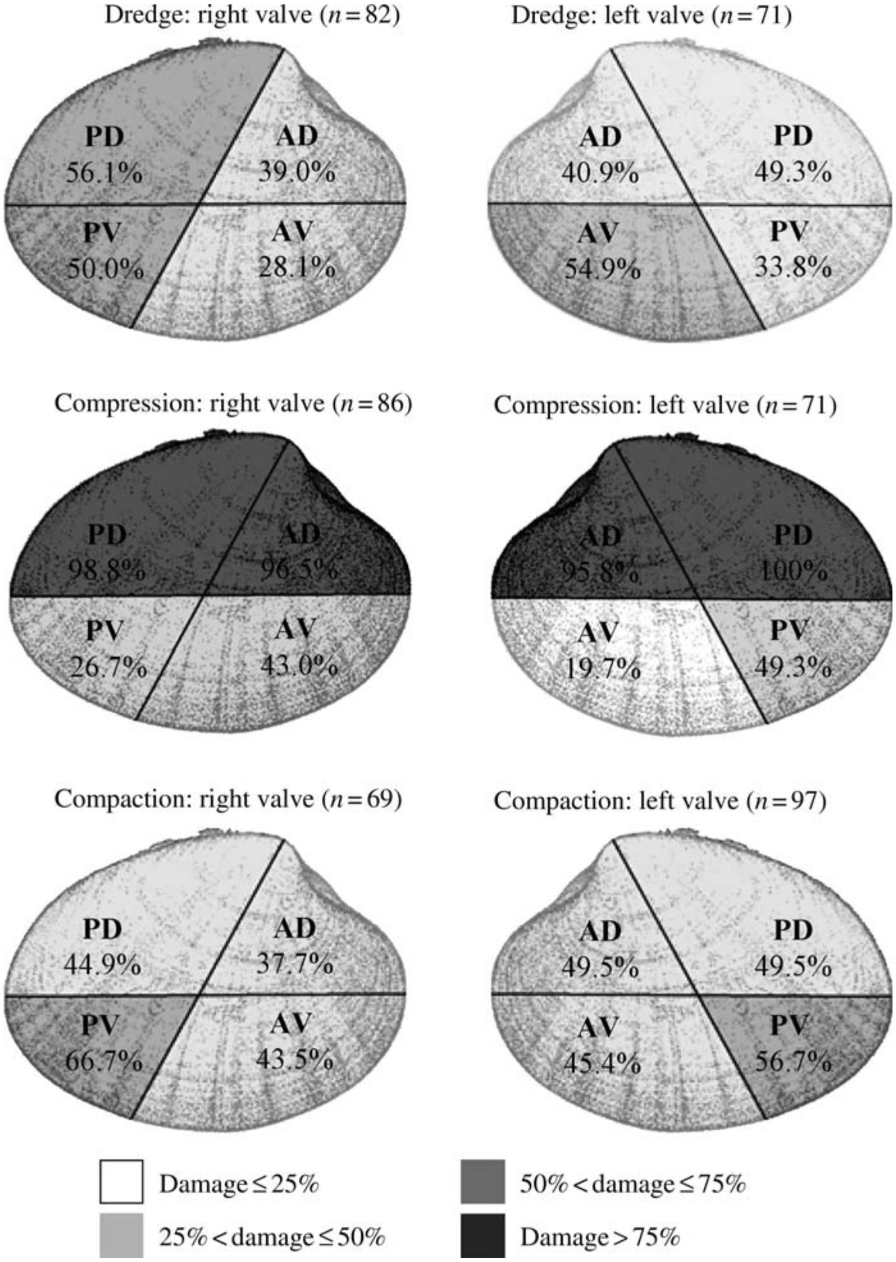

Figure 5. Frequency distribution of damaged areas detected in *C. chione* shells (right and left valves) during bivalve dredging, compression, and compaction experiments. AD, anterior dorsal; PD, posterior dorsal; AV, anterior ventral; PV, posterior ventral.

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The frequency distribution of damaged areas (AD, PD, AV, and PV) detected in each shell (right and left valves from the dredge, compression, and compaction experiments) is shown in Figure 5. In samples taken from the dredge, the most frequently damaged areas of the right valve were PD (56.1%) and PV (50.0%) and of the left valve AV (54.9%). In compression experiments, most shells had damage in the AD (96.5 and 95.8% for right and left valves, respectively) and PD areas (98.8 and 100% for right and left valves, respectively). In compaction experiments, shells were mainly damaged in the PV area (66.7 and 56.7% for right and left valves, respectively).

In all, 15 breakage patterns were registered in the whole sample, 14 in the dredged material, 7 in compression experiments, and 12 in compaction experiments. The most common fracture patterns in dredged bivalves were AD–PD and PD–PV (both with 16.3%). Pattern AD–PD dominated the right valve (20.7%) and PD–PV the left valve (16.9%). In compression experiments, the most frequent fracture pattern in both valves was AD–PD, with a prevalence of 40.1% (37.2 and 43.7% for right and left valves, respectively). In compaction experiments, the most usual breakage patterns were AV–PV in the right valve (31.9%) and AD–PD in the left valve (30.9%).

Simulations using the FEM

Computerized simulations of the forces exerted in the three-dimensional model of the *C. chione* shell are illustrated in Figure 6. FEM allowed visualization of the spatial distribution of the forces in the shell, and as expected, revealed that compression forces were concentrated in the area of greatest convexity of the shell, so coinciding with the point where compressive loading was exerted (Figure 6a). In contrast, compactional forces were more dispersed over the entire shell surface, and the highest pressures and tensions were in areas closest to the edge of the shell (Figure 6b).

Discussion

The forces required to break *C. chione* shells were much lower in point-loading experiments than in compaction experiments, reflecting the smoothing effect of the sand layer and the dissipation of the compactional force over the entire shell surface. Interspecific comparisons of shell strength need to be interpreted cautiously owing to the different and wide size ranges of the bivalves subjected to shell-strength measurements. Nevertheless, our experiments revealed that the shell strength of *C. chione* compares favourably with most values reported in the literature for compression experiments with other bivalve species (Table 2). Indeed, *C. chione* has a very strong and resistant shell, unlikely to be cracked and broken easily during dredging. This further confirms the fact that the forces generated by clam dredges are considerable and that the progressive installation of more-powerful engines in the commercial dredge fleet has had implications in terms of fishing impact and shell damage. Similarly, structural changes in the beam-trawl fleet of the North Sea, in terms of a marked increase in engine power and consequent faster fishing speed, led to increased damage to *Arctica islandica*, as revealed by the higher incidence of shell scars (Witbaard and Klein, 1994). Moreover, a positive correlation has been documented between fishing intensity of the scallop dredge fleet and the frequency of shell scars in *Glycymeris glycymeris* (Ramsay *et al.*, 2000).

Shell strength is an adaptation to stresses, and results from selection among genetically determined phenotypes in populations, but can also be ecophenotypic, i.e. induced within an individual's lifetime (Zuschin *et al.*, 2003). Moreover, a shell's resistance to breakage depends on a broad range of shell features, including size, weight, thickness, shape, sculpture and ornamentation, microstructure and organic matrix, and taphonomic variables, such as taphonomic grade, presence of drill holes, and progressive degradation of the skeleton and organic matrix (LaBarbera and Merz, 1992; Zuschin and Stanton, 2001; Zuschin *et al.*, 2003, and references therein). As the individual contributions of these parameters are difficult to discern, shell strength appears to be extremely variable when measured experimentally (Taylor and Layman, 1972; Kontrovitz *et al.*, 1998; Zuschin *et al.*, 2003).

Morphological variables are highly correlated in a mollusc's shell, either linearly or exponentially. Similarly, significant correlations between morphological variables (SL, SH, width, shell curvature, Sw, and ST, and Tw) and shell strength during compression experiments have been reported for several bivalves (e.g. Miller *et al.*, 1994; Witbaard and Klein, 1994; Coffen-Smout, 1998; Gilkinson *et al.*, 1998; Zuschin and Stanton, 2001; Beadman *et al.*, 2003; Grefsrud and Strand, 2006). When subjected to compressive forces, all these bivalves invariably displayed positive correlations between shell morphometric variables and shell strength, demonstrating that shell resistance to breakage increases as a function of animal size and weight.

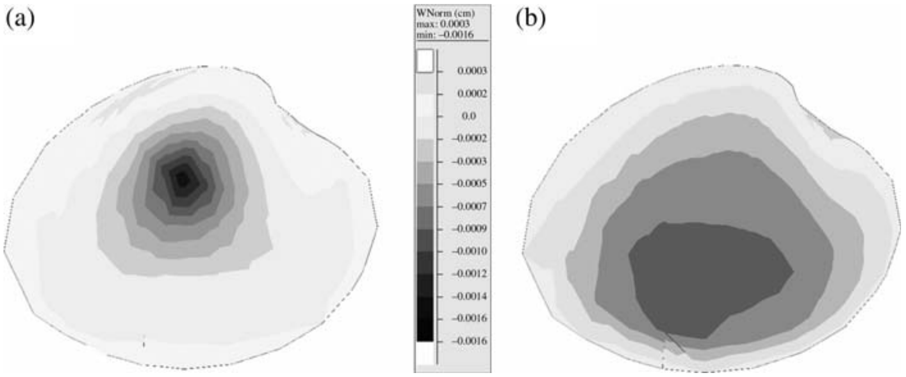

Figure 6. Simulations of the distribution of the forces in the three-dimensional model of *C. chione* shell through the FEM: (a) compression experiment; (b) compaction experiment. In both simulations, darker colours indicate the areas of the shell subjected to greater tension and traction.

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Table 2. Comparison of shell strength between the smooth clam (*C. chione*) and other marine and freshwater bivalve species.

Species	**Shell strength (N)**	**Reference**
Callista chione (Linnaeus, 1758)	580 ± 318 (39 – 1743)[a] 3265 ± 1046 (1068 – 5831)[b]	Present study
Arctica islandica (Linnaeus, 1767)	300 ± 64 to 800 ± 345[c]	Witbaard and Klein (1994)
Astarte borealis (Schumacher, 1817)	205.7 – 253.0	Gilkinson *et al.* (1998)
Cerastoderma edule (Linnaeus, 1758)	12.9 ± 4.1 to 171.4 ± 15.9[d]	Coffen-Smout (1998)
Clinocardium ciliatum (Fabricius, 1780)	32.9 – 117.0	Gilkinson *et al.* (1998)
Corbicula fluminea (O.F. Müller, 1774)	177[e] 118[e]	Kennedy and Blundon (1983) Miller *et al.* (1994)
Cyclocardia novangliae (Morse, 1869)	30.0	Gilkinson *et al.* (1998)
Cyrtodaria siliqua (Spengler, 1799)	74.7	Gilkinson *et al.* (1998)
Dreissena polymorpha (Pallas, 1771)	22[e]	Miller *et al.* (1994)
Fusconaia ebena (I. Lea, 1831)	806[e]	Miller *et al.* (1994)
Ischadium recurvum (C.S. Rafinesque, 1820)	5 – 21[f]	Blundon and Kennedy (1982)
Macoma balthica (Linnaeus, 1758)	1 – 88[f]	Blundon and Kennedy (1982)
Macoma calcarea (Gmelin, 1791)	4.1 – 56.2	Gilkinson *et al.* (1998)
Macoma mitchelli (Dall, 1895)	1 – 8[f]	Blundon and Kennedy (1982)
Mulinia lateralis (T. Say, 1822)	2 – 20[f]	Blundon and Kennedy (1982)
Mya arenaria (Linnaeus, 1758)	2 – 59[f] and 2 – 227[g]	Blundon and Kennedy (1982)
Congeria leucophaeata (Conrad, 1831)	4 – 8[f]	Blundon and Kennedy (1982)
Mytilus galloprovincialis (J.B. Lamarck, 1819)	63.4 – 152.6[h]	Webb and Korrûbel (1994)
Pecten maximus (Linnaeus, 1758)	107 – 330[i] and 71 – 137[j]	Grefsrud and Strand (2006)
Rangia cuneata (Sowerby, 1831)	8 – 680[g]	Blundon and Kennedy (1982)
Tagelus plebeius (Lightfoot, 1786)	3 – 78[g]	Blundon and Kennedy (1982)

[a] Compression experiments.
[b] Compaction experiments.
[c] According to SH categories.
[d] According to size class and striking point.
[e] SL = 20 mm.
[f] SL < 50 mm.
[g] SL < 90 mm.
[h] According to the provenance (wild or farmed populations) and degree of infestation.
[i] Wild population.
[j] Farmed population.

In our study, positive correlations were always obtained in the compression experiments and negative correlations in the compaction experiments, meaning that the shell strength of *C. chione* increased with clam size in point-load tests and decreased with clam size in compaction tests. The positive correlations in compression experiments corroborate the information available for several other bivalve species, and the negative correlations in compaction experiments are probably attributable to the spreading of the compactional force in the sand layer and the dissipation of energy throughout the whole shell surface. Consequently, as smaller bivalves have less surface area exposed to compactional force, their shells are stronger and more resistant to breakage than larger bivalves. Similar results were found for *A. islandica* damaged by bottom trawling, with the percentage of damaged shells increasing with size, meaning that smaller shells resist greater forces than larger shells (Rumohr and Krost, 1991).

Shell strength as a function of morphometric parameters is highly variable within and between taxa, showing that it is a compromise among a multitude of functions and reflects the multifunctionality of a shell (Currey, 1988). Therefore, shell strength can only be evaluated adequately in relation to ecology and life history (Zuschin and Stanton, 2001; Zuschin *et al.*, 2003). In our experiments, the most effective predictors of shell strength were ST in compression experiments and Sw in compaction experiments. Similarly, in *Anadara ovalis*, *Mercenaria mercenaria*, and *Mytilus edulis*, ST was the best predictor of compressive shell strength (Zuschin and Stanton, 2001). Although shell strength is typically correlated with size (generally expressed as length, width, and height, or less frequently as volume or weight), its correlation with ST is usually stronger, i.e. shell strength is better predicted by ST than by size (Currey, 1988; Zuschin and Stanton, 2001; Zuschin *et al.*, 2003). ST may be a constitutive (genetically determined) or induced defence mechanism (ST increases more with predation intensity than with size; Zuschin *et al.*, 2003) and is important for survival, likely the most reliable defence against predation (Zuschin and Stanton, 2001). Indeed, because thicker shells are stronger, heavier, and more difficult to dislodge and manipulate, ST is an obvious protection against shell-breaking and shell-boring predators (Currey, 1988; Zuschin and Stanton, 2001; Zuschin *et al.*, 2003, and references therein).

The FEM simulations using the three-dimensional replica of the *C. chione* shell strongly support the data on the most frequently damaged areas and breakage patterns observed in bivalves subjected to shell-strength measurements. First, in compression experiments the most frequently damaged areas of the shell were AD and PD (near the umbo and next to the point where compressive loading was applied), whereas in compaction experiments, the most frequently damaged area of the shell was PV (closer to the shell edge and the area under most pressure). Additionally, the most frequent fracture pattern was AD–PD in compression experiments (along the dorsal side of the shell, near the umbo) and AV–PV in compaction experiments (along the ventral side, close to the shell edge). Finally, the lower diversity of breakage patterns in compression tests (seven patterns) than in compaction

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tests (12 patterns) certainly relates to the different distribution of forces and tensions in both experiments, with compressive force concentrated around the area where the point-load was applied and compactional force spread over the entire shell surface.

Breakage patterns differ considerably within and between taxa, and examples of bivalve species displaying highly diverse breakage patterns after compression experiments include *A. ovalis*, *M. mercenaria*, and *M. edulis* (Zuschin and Stanton, 2001). Generally in compression experiments, it is difficult to correlate fracture patterns with shell morphometrics and shell strength, because even applying force consistently at the same location on the shell surface causes heterogeneous breakage patterns (Zuschin and Stanton, 2001; Zuschin *et al.*, 2003). In compaction experiments, however, shell fragmentation is controlled by mechanical shell strength and by extrinsic factors, including sediment type (grain size), burrowing depth, and orientation (Zuschin *et al.*, 2003). Nevertheless, despite all shells fragmenting differently, the fracture patterns do provide valuable information about vulnerable parts and specific breakage mechanisms (Zuschin *et al.*, 2003), which in this case might be helpful in understanding how *C. chione* shells are damaged during dredging.

Some studies have indicated that tooth spacing does not affect dredge selectivity or the number of damaged bivalves caught, because the tooth bar acts like a hoe and bivalves enter the dredge without passing through the space between the teeth, virtually without being touched and damaged by the teeth (Gaspar *et al.*, 2002). Such a conclusion is supported by the results of the present study, because the analyses of damage areas and breakage patterns revealed two main groupings of samples, one with the bivalves from compression experiments and the other with bivalves from commercial dredging and compaction experiments. Clearly, therefore, there is a similarity in the type of damage inflicted during dredging and that obtained in simulated compaction of shells within the sediment. The results confirm that most of the shell damage suffered by *C. chione* during dredging takes place in the sediment, as a consequence of compaction of the sand on burrowed bivalves by the toothed bar of the dredge and not through direct impact of teeth on the shells. In fact, shell damage (e.g. broken or smashed valves) is greater within the sediment when the dredge moves through the substratum, and less (e.g. chipped margins and disjoint umbos) as a result of contact and abrasion between bivalves, between bivalves and debris, and/or between bivalves and the metallic grid (Gaspar *et al.*, 2001).

Improvement in the design of bivalve dredges

Understanding the interaction between mobile fishing gear and infaunal bivalves implies combining elements of the seabed (e.g. sediment type, grain size) with key biological/ecological parameters of the species (e.g. shell size, surface of impact, burrowing depth, and orientation), all of which play a role in determining the damage to the animals caused by dredges (Witbaard and Klein, 1994; Gilkinson *et al.*, 1998). Therefore, scientists can make notable contributions by working together with gear technologists to develop benthos-friendly gear that is lighter, more hydrodynamic, and less physically damaging to the target species (Gilkinson *et al.*, 1998).

The experiments and simulations here have provided information potentially useful in improving the design, construction, and performance of mechanical dredges for bivalves and might help in due course decrease the number of bivalves being damaged. Nevertheless, it is stressed that despite the experiment being a seemingly realistic approach to what happens during bivalve dredging, the present experiments, computer models, and simulations in the laboratory are inevitably different from reality in the field. First, the shell strength of live bivalves might differ slightly from those without soft tissues because of the opposing effects of internal hydrostatic pressure and adductor muscles (Coffen-Smout, 1998), although the *C. chione* shell-failure loads measured herein provide indicative information on the forces required to damage shells over the size range caught in the commercial fishery, potentially useful information for designers of bivalve dredges. Additionally, sediment type and grain size need to be taken into account whenever analysing data from compaction experiments, because sediment features may differ between bivalve beds. This is crucial because fine-grained sediments retain large quantities of water and might jeopardize compaction results as a consequence of water movement and pore-volume reduction, whereas coarse-grained sediments are more resistant

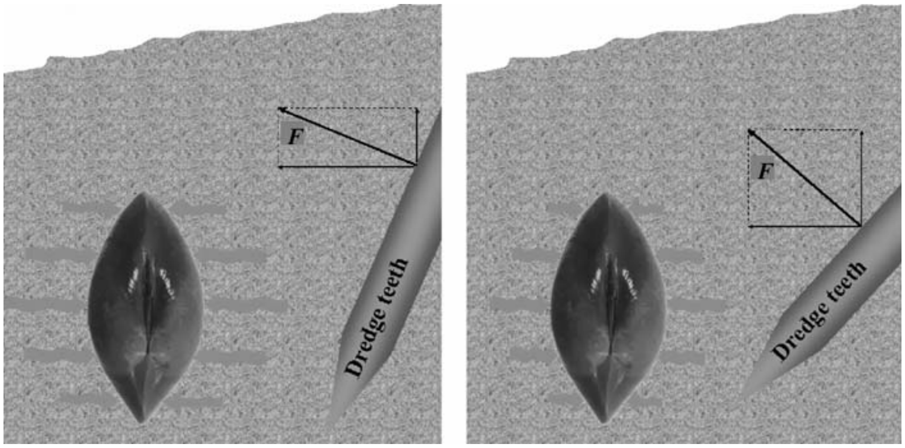

Figure 7. Illustration of the improvement in bivalve dredge design by increasing the length and angle of the teeth in the dredge mouth, aimed at reducing and distributing differentially the compaction force within the sediment, and compelling upward movement of burrowed *C. chione* (compare the direction of the forces for different angles of the teeth: left and right panels are the present and the proposed design, respectively).

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to compaction as a result of the supporting effect of the grains and the lower pore-water volume (Zuschin and Stanton, 2001; Zuschin *et al.*, 2003).

In conclusion, and in terms of modification of the dredge design currently used by the commercial dredge fleet, a possible solution aimed at minimizing clam damage would be to increase both the length and the angle of the teeth in the mouth of the dredge, hence reducing the compaction force and distributing it differentially within the sediment (increasing it towards the lower side and moderating it nearer the top), forcing upward movement of both the sand and the burrowed bivalves (Figure 7). Hopefully, such a modification in gear design would allow shell damage to be reduced and the indirect fishing mortality of *C. chione* minimized, leading to long-term sustainable exploitation of this bivalve.

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