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Shell structure and shell strength in Cirripedes

A A KARANDE and M UDHAYAKUMAR
Biology Division, Naval Chemical and Metallurgical Laboratory, Tiger Gate, Bombay 400 023, India

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Abstract. Compressive and adhesive strengths of 7 barnacles endemic to Bombay shore were ascertained by using Instron universal testing machine. The adhesive strengths of balanid species settled on man-made materials like bakelite, asbestos, perspex, rubber, glass and teflon were determined. The adhesion on teflon was found to be the poorest. Comments are made on the compressive strengths of barnacles and their shell macro-structures. A need for the adoption of uniform method of the preparation of shell samples as well as of instrumental technique has been suggested for computing fresh data for the representative species.

Keywords. Mechanical strength; tropical barnacle; marine; man-made material.

1. Introduction

Attempts are currently made to evolve an antifouling technology that is free from use of chemical toxins like cuprous oxide and tributyl-tin oxide. Use of low energy surface materials or coatings is considered as one of the promising areas of research (Young and Crisp 1982). If this approach is to be proved effective, then the biological studies having relevance to the adhesion and bioadhesives of the fouling organisms should receive more attention. This aspect of study has relevance also to the maintenance of marine structures which are not easily approachable and need periodical manual or mechanical cleaning (Devoluy *et al* 1972).

Earlier reports on the assessment of compressive and adhesive strengths of barnacles have bearing on host-predator relationship (Qasim 1957; Palmer 1982) and on shell strength and wave action (Gubbay 1983; Barnes *et al* 1970; Murdock and Currey 1978). Some of the important publications describing the shell structure in acorn barnacles are by Cornwall (1956, 1958, 1959, 1960), Costlow (1956), Read (1960), Stubbings (1967), Ross (1970, 1971), Newman and Ross (1971), Bourget and Crisp (1975), Klepal and Barnes (1975) and Otway and Anderson (1985). Udhayakumar and Karande (1986) have reported adhesive strengths of balanid and chthamalid barnacles.

The present work was carried out with a view to adding some more information to the existing literature on barnacle adhesive and compressive strengths. Report on shell design and architecture of 8 barnacle species endemic to Bombay shore is communicated elsewhere for publication.

2. Materials and methods

In the present study, the methods adopted by Barnes *et al* (1970), Bourget (1977), Murdock and Currey (1978) and Gubbay (1983) were generally followed. Seven species of barnacles viz. *Balanus amphitrite amphitrite* (Darwin), *B. variegatus*

(Darwin), *B. amaryllis euamaryllis* (Broch), *Chthamalus malayensis* (Pilsbry), *Ch. withersi* (Pilsbry), *Tetraclitella karandei* (Ross) and *T. purpurascens* Wood settled on boulders were examined for the tension and compression strengths.

2.1 *Tension (adhesive) tests*

For recording the adhesive strengths, Instron model 1123 universal testing machine was used. The apparatus consisted of a strain gauge load cell secured to a moving cross-head. A stainless steel wire was glued to a solitary shell with the help of araldite resin. During the experiment the barnacle with its substrate was held securely in a vice and a hook of the embedded wire was interlocked with the wire hook held in the jaws fitted on the cross-head of the equipment. The experiments were carried out at a constant cross-head speed and the maximum load borne prior to catastrophic failure i.e. the detachment of the shell from the substratum, was recorded.

2.2 *Compression tests*

For compression testing i.e. loading from above over the shell, the same Instron equipment was used. The individual barnacle settled on a substratum was held in a vice with its opercular plates lying horizontal and the load applied on the shell by flat stainless steel cylinder secured to a moving load cell. The maximum load borne before shell failure by breakage was recorded.

3. Results

3.1 *Shell design and architecture*

There are no reports on macrostructure of the shells of Indian barnacles. Recently Udhayakumar (1988) examined shell sculpturing of the species endemic to Bombay shore. A short account of macrostructure of megabalanus *B. t. tintinnabulum* is given below. This will assist in acquaintance with the terminology used in shell architecture and shell strength described in the following sections.

In *B. t. tintinnabulum* the parietal plates at apical (figure 1A), middle (figure 1B) and at basal level (figure 1C) show lap, scarf and butt joints respectively.

The carinal margin of each radius having distinctive bipinnate teeth is received along the edge of the adjoining plate (figure 1D). It shows good interlocking with elaborately sculptured edge of the adjacent pariete (figure 1E). The radial margin is in firm attachment with the entire height of the adjoining plate. The sculpturing of alar-rostral margin (figure 1F) is not elaborate. Each pariete shows a row of longitudinal hollow canals (figure 1B). Each longitudinal septum of the pariete is elaborated into massive wedge shape pinnate process (figure 1C) that sits in hollow of the radial canal of the basal plate at the junction of the basal plate and parietes.

The secondary septae originating from the inner side of the outer lamina of parietes are simple spiny projections (figure 1C).

Calcareous basal shell plate is thick particularly along the circumference. The base is traversed by main radiating canals (figure 1C) and several smaller secondary canals. All these radiating canals are septate.

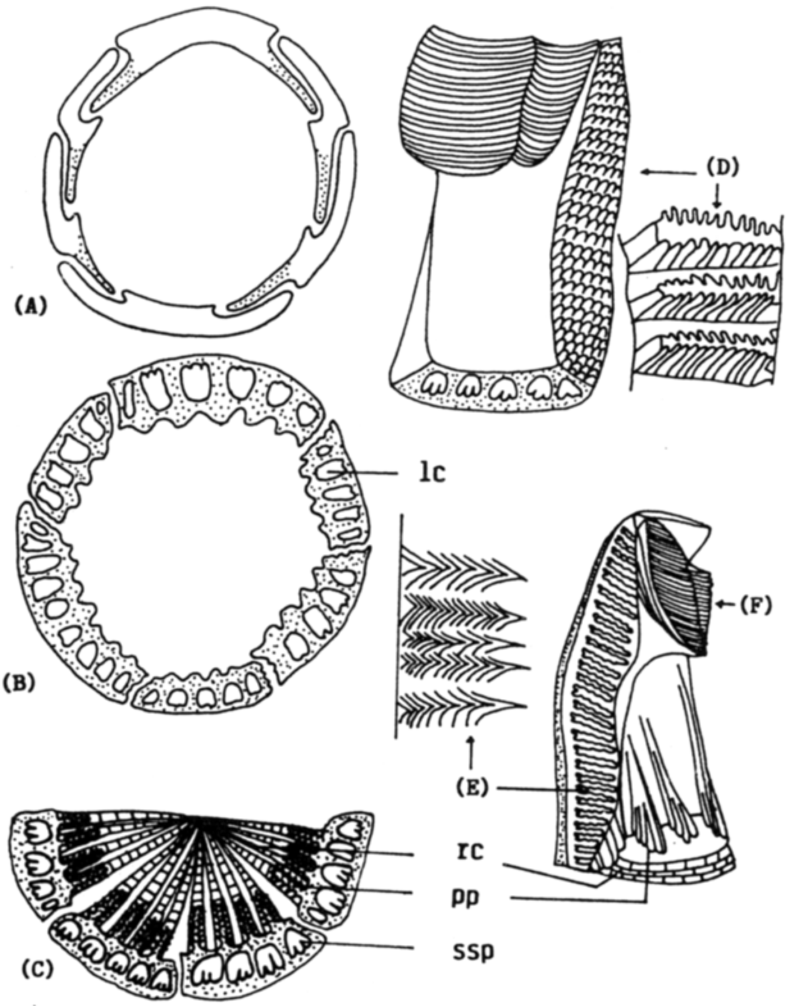

Figure 1. *B. t. tintinnabulum*, semidiagrammatic macrostructure of shell. A–C. Transverse sections of shell at apical (A), middle (B) and basal level (C). D. Carinal margin of radius. E. Groove along the edge of the paries of the carina. F. Ala-rostral margin.
(lc, Longitudinal canal; pp, pinnate process of longitudinal septa; rc, radial canal; ssp, secondary spinose processes or teeth.)

3.2 *Compression strengths of barnacles*

In this part of the study, 5 species viz. *B. a. amphitrite*, *B. variegatus* (calcareous base), *T. karandei*, *Ch. malayensis* and *Ch. withersi* (membranous base) were chosen. No observations could be made on *B. t. tintinnabulum* and on *B. a. euamaryllis* because of their scanty presence on boulders in the coastal waters of Bombay.

Figure 2 illustrates the regression lines drawn from the data obtained on the maximum load borne by 5 species under compression loads applied. Table 1 gives a comparison of the strengths of shells under compression in different species. It is observed from this table that the compressive strengths of 4 species, including both

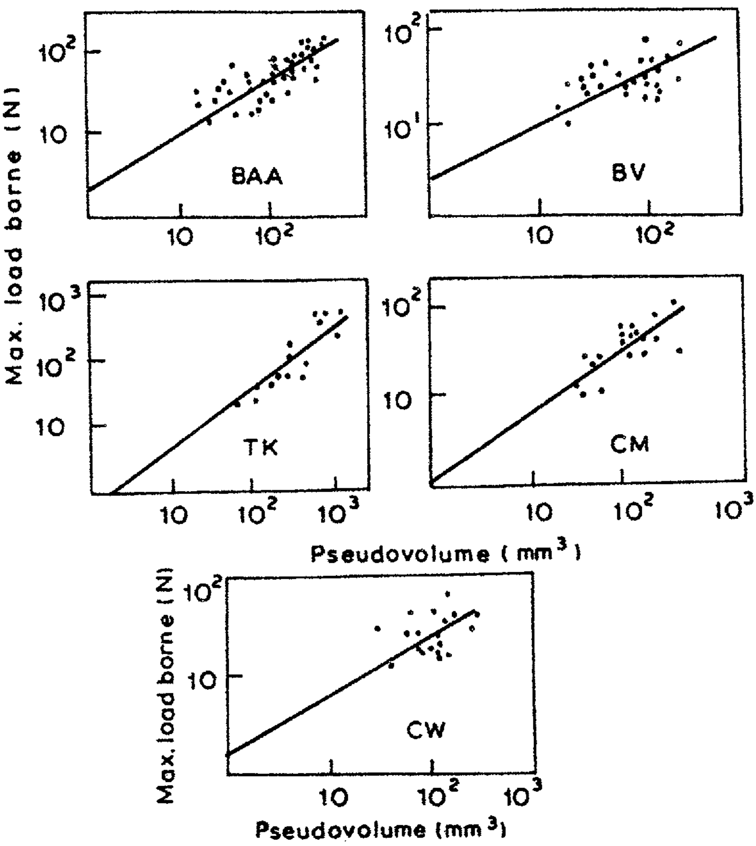

Figure 2. Compression load (N) required to bring about catastrophic failure of shells of solitary barnacles.
(BAA, *B. a. amphitrite*; BV, *B. variegatus*; TK, *T. karandei*; CM, *Ch. malayensis*; CW, *Ch. withersi*).

Table 1. A comparison of the shell strengths under compression of various species of barnacles.

Species	Pseudo volume (mm^3)	Maximum load borne (N) prior to shell failure: Solitary	Maximum load borne (N) prior to shell failure: Crowded
B. a. amphitrite	100	46·77	—
B. variegatus	100	36·47	—
T. karandei	100	39·81	101·62
Ch. malayensis	100	41·30	61·94
Ch. withersi	100	25·82	42·36

The maximum load values are taken from the regression lines fitted to the data.

calcareous base and membrane base, are comparable (between 36·47–46·77 N/ 100 mm^3). Only one chthamalid *Ch. withersi* shows poor compressive strength as compared to the others. A compressive strength of *Ch. malayensis* is very close to that of *B. a. amphitrite* and is even more than that of *B. variegatus*. Again compressive strengths of calcareous base *B. variegatus* and membrane base *T. karandei* are comparable.

The compressive strengths of individual or a single *Ch. malayensis*, *Ch. withersi* and *T. karandei* growing in crowds were also recorded so as to ascertain if the support offered by the neighbouring individuals contributed to the enhancement of load bearing capacity of an individual member in the crowd. It is observed from table 1, that all these barnacles show a very notable increase in their capacity to bear load as compared to the individuals of the same species growing in isolation. *T. karandei*, *Ch. malayensis* and *Ch. withersi* show 155, 55 and 64% improvement respectively in their load bearing abilities in crowded settlements.

3.3 *Tensile (adhesion) strengths of barnacles*

Seven species of barnacles including *B. a. euamaryllis* were tested under tension for assessing their adhesive strengths on the rocky substratum they had attached. Adhesive strength of *B. variegatus* settled on bakelite surface was recorded since the specimens settled on rocky surface were not available in coastal waters. The results obtained are based on the examination of 30–60 individuals of each species tested.

It is observed from table 2 that the adhesive strength of *B. a. amphitrite*, amongst the species studied, is the highest ($1{\cdot}133 \times 10^8$ N m^{-2}), followed by that of *B. variegatus* and others. The adhesive strength of *T. purpurascens* has been found to be the least ($0{\cdot}12 \times 10^8$ Nm^{-2}). The adhesive strength of *B. a. amphitrite* is about 90% more than that of membrane base *T. purpurascens*. Generally barnacles having membranous bases show inferior adhesive strength than those with calcareous bases. However, a megabalanus, *B. a. euamaryllis* having a calcareous base also shows poor adhesive strength.

At a probability level of $P < 0{\cdot}10$, no significant difference in strengths of two balanids *B. a. amphitrite* and *B. variegatus* was noted. *B. a. amphitrite*, however showed significantly higher bonding strength as compared to all other species ($P < 0{\cdot}00005$). *B. a. euamaryllis* showed significantly more adhesive strength as compared to all membranous base chthamalids and tetraclitid but interestingly its

Table 2. Average adhesive strength (Nm^{-2}) of various species of barnacles settled on natural substrate.

Species	Average adhesive strength Nm^{-2} ($\times 10^8$)	Habitat
B. a. amphitrite	1·133	Intertidal
*B. variegatus**	0·860	Open sea
B. a. euamaryllis	0·268	Open sea
T. karandei	0·199	Neritic
T. karandei (on barnacle shell)	0·280	Neritic
Ch. withersi	0·149	Neritic
Ch. malayensis	0·131	Neritic
T. purpurascens	0·120	Neritic

**B. variegatus* settled on bakelite surface.

adhesion was found to be poorer than that of tetraclitilid *T. karandei* ($P < 0{\cdot}005$ to $P < 0{\cdot}00005$).

It is observed that the adhesive strength of *T. karandei* individuals settled on *B. a. euamaryllis* shell was superior to that of the individuals of the same species settled on rocky substrate.

3.4 *Adhesion on man-made substrates*

The adhesive strengths of two species viz. *B. a. amphitrite* and *B. variegatus*, very commonly encountered on various man-made materials, were examined. Two sets of coupons of various man-made materials were immersed in the seawater, each for periods of 35 and 85 days respectively to obtain individuals of varying ages for testing. It is observed from table 3, that the force required to dislodge both of these species is the highest for either glass or bakelite coupons, whereas it is the least in case of teflon coupons. The values obtained on rubber surface are not considered dependable for comparisons.

It has earlier been noted by Yule and Walker (1984) that a rough surface provides better opportunities for barnacle cyprids to achieve firm settlement. However, once having settled and grown to young adult, no particular benefit seems to be derived in securing a stronger bondage.

4. Discussion

4.1 *Compression strength*

Some of the easily recognisable shell features which contribute to its strength are the thickness of wall plates (Bourget 1977), plate porosity which arrests crack growth

Table 3. Average force (Nm^{-2}) required to dislodge two species of barnacles from various man-made surfaces.

	B. a. amphitrite		*B. variegatus*	
	35 days	85 days	35 days	85 days
Surface	$\times 10^8\ Nm^{-2}$			
Teflon	0·0133 ± 0·0002	0·0313 ± 0·017	0·0115 ± 0·0003	—
Perspex smooth	0·35 ± 0·04	0·42 ± 0·03	—	0·15 ± 0·02
Perspex roughened	0·41 ± 0·01	0·178 ± 0·04	—	0·116 ± 0·016
Glass	0·67 ± 0·06	1·17 ± 0·14	0·60 ± 0·11	0·61 ± 0·04
Slate	0·59 ± 0·05	0·57 ± 0·02	0·48 ± 0·05	0·51 ± 0·03
Bakelite smooth	0·67 ± 0·06	0·94 ± 0·06	0·64 ± 0·04	0·86 ± 0·10
Bakelite roughened	0·51 ± 0·07	0·90 ± 0·07	0·59 ± 0·02	0·66 ± 0·06
Asbestos	0·51 ± 0·03	0·89 ± 0·03	0·51 ± 0·03	0·34 ± 0·02
Rubber	—	0·74 ± 0·05	0·61 ± 0·05	0·58 ± 0·03

(Barnes *et al* 1970), ridges or crenulations on plates (Murdock and Currey 1978), interlocking between parietes and base (Newman *et al* 1967; Murdock and Currey 1978) and the cuticle covering the shell plates (Parke and Moore 1935; Bonar 1936; Newman and Ross 1971). Besides these the strengthening of the plates by interspacing of organic tissue in the matrix of shell is also known to contribute to shell strength (Newman *et al* 1967).

Gubbay (1983) divided 7 temperate species into 3 groups viz. strong, intermediate and weak as regards their compressive strengths. He identified *Balanus balanus* having a compressive strength of 145 N/100 mm^3 as a strong barnacle. *B. crenatus* (calcareous base), *Eliminus modestus*, *Semibalanus balanoides* and *Ch. montagui* (all membrane base) having strengths between 35 and 57 N/100 mm^3 were categorised as intermediate ones. And *Verruca stroemia* (membrane base) having load bearing strength of 23 N/100 mm^3 was categorised as a weak barnacle. He observed that the species having membranous bases generally lacked the compressive strength.

Amongst the present Indian species, *B. a. amphitrite*, *B. variegatus* and *B. kondakovi* have comparable shell structures as well as interlocking sculpturing as that of *B. balanus* but have thinner wall plates and bases. These barnacles show less compressive strengths as compared to *B. balanus*. The importance of having thicker plates in addition to strong junctional interlockings therefore is obvious.

B. balanus which is shown to have a good compression strength, resembles *B. t. tintinnabulum* in its interlocking architecture between the individual parietes. Some variations, however, do exist. In *B. t. tintinnabulum* the sculpturing of the carinal margins of radii is more elaborate than that of *B. balanus* (Karande A A and Udhayakumar M, unpublished results). In both these species the longitudinal septae terminate into elaborate pinnate processes but in *B. t. tintinnabulum* secondary pinnate processes are absent. The parietes of *B. balanus* are not as heavy as *B. t. tintinnabulum*, but have heavily built ridges on inner and outer surfaces. *B. balanus* unlike *B. t. tintinnabulum* does not have radial canals in the basal plate and the depressions for receiving the pinnate processes of longitudinal septae are restricted to the periphery of the base. Comparison of the compressive strengths of these two species would therefore be worthwhile.

In the present study it was observed that the 4 members of 3 different genera *B. a. amphitrite*, *B. variegatus*, *T. karandei* and *Ch. malayensis* bore maximum load varying between 40–47 N/100 mm^3. No difference in strength between calcareous and membrane base barnacles was thus evident.

Despite a very elaborate sculpturing between the junctions, the presence of porous parietes as well as calcareous bases, *B. a. amphitrite* and *B. variegatus* show only 'intermediate' compressive strengths. On the other hand *Ch. malayensis* which lacks calcified base, porosity of parietes and pinnate ridges of the longitudinal septae, possesses load bearing capacity comparable to *B. a. amphitrite*. Its load bearing strength therefore is probably associated with heavily ribbed parietes. Membrane base *T. karandei* also has an 'intermediate' load strength and this can be attributed to its heavily ribbed surface, tubular parietes and with firm interlockings between adjoining parietal plates.

The above observations suggest that no one or two structural features contribute to shell strength. Species like *B. a. amphitrite* having all essential features for securing firm adherence amongst plates and between the latter and the base, may fail in loading because of their thin parietal plates. On the other hand membrane base *Ch. malayensis* and *T. karandei* which lack good junctioning features may show a loading capacity comparable to *B. a. amphitrite* because of their heavily ribbed parietes. Barnes *et al* (1970) attributed loading strength of *Ch. stellatus* to its heavily ribbed parietes. They observe that 'the barnacle shell is a complex structure and its mechanical strength is dependent not only upon that of the individual parts but upon their structural relations and adhesion to one another'. Computation of what shell attributes of *Ch. malayensis* and *T. karandei* make these species as strong as *B. a. amphitrite* or *B. variegatus* would be a worthwhile study. Furthermore *T. karandei* has a distinctive sculpturing on the carinal edges of radii, it shows several short porous tubes in parietes, its walls are ribbed and has tubiferous finger-like extensions of radii around opercular opening (Ross 1971). Despite these shell features, its compressive strength is no better than that of *Ch. malayensis.*

Besides intrinsic shell characters, a crowding also enhances load bearing capacity of an individual barnacle as noted by Gubbay (1983) amongst *S. balanoides*. This was found to be true in 3 species examined in this study.

4.2 *Adhesive strength*

Barnacles secure adhesion with the help of continuously produced cementing material. Gubbay (1983) observed that the membrane base species secured more adhesion than the barnacles having calcified bases. In the present study 2 species viz. *B. a. amphitrite* and *B. variegatus* showed stronger adhesion than each of the 4 membrane base species. Interestingly a megabalanus *B. a. euamaryllis* showed the least adhesion as compared to other calcareous base barnacles. It is likely that as the basal plate of this balanid grows in size, the earlier laid cement loses its bonding strength. This might as well be true of the barnacles examined by Gubbay (1983). The age factor perhaps is relevant.

As reported earlier by several workers (Bultman *et al* 1984; Crisp and Walker 1987), the adhesion of barnacles on teflon surface was observed to be poorer as compared to the other surfaces. That a surface has some role to play in securing adhesion was also revealed by the fact that a better adhesion by individuals was achieved on barnacle shell than on rocky substratum.

Compressive and adhesive strengths of acorn barnacles have been determined by several workers adopting more or less an identical instrumental method. Minor variations, however, do exist in the preparation of the test samples as well as in the details of the measurement techniques. As a result of this, correlating the mechanical strength of barnacle with its shell architecture has become difficult. Therefore there is a need of adopting a uniform approach for recomputing fresh data for the representative species.

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