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Quantifying the attachment strength of climbing plants: A new approach

Tina Steinbrecher [a], Elisabeth Danninger [b], Deane Harder [b], Thomas Speck [b], Oliver Kraft [a], Ruth Schwaiger [a,*]

[a] Karlsruher Institut für Technologie (KIT), Institut für Materialforschung und Institut für Zuverlässigkeit von Bauteilen und Systemen, Postfach 3640, 76021 Karlsruhe, Germany
[b] Albert-Ludwigs-Universität Freiburg, Faculty of Biology, Plant Biomechanics Group, Botanic Garden, Schänzlestrasse 1, 79104 Freiburg, Germany

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ABSTRACT

In order to grow vertically, it is essential for climbing plants to firmly attach to their supporting structures. In climbing plants, different strategies for permanent attachment can be distinguished. Besides twining stems and tendrils, many plants use attachment pads or attachment roots for this purpose. Using a novel custom-built tensile testing setup, the mechanical properties of different permanent attachment structures of self-clinging plant species were investigated, namely the attachment pads of Boston ivy (*Parthenocissus tricuspidata*), the attachment roots of ivy (*Hedera helix*) and the clustered attachment roots of trumpet creeper (*Campsis radicans*). Force–displacement measurements of individual attachment pads as well as of complete structures consisting of several pads or roots were conducted for both natural and laboratory growth conditions. The shapes of the curves and the maximum forces determined indicate clear differences in the detachment process for the different plants and structures tested. Based on these findings, it is argued that the attachment structures are displacement-optimized rather than force-optimized.

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1. Introduction

A good grip or firm anchorage is essential for the survival of not only sessile creatures but also many motile organisms to provide an effective locomotion and safe standing. Animals and plants have evolved numerous solutions to ensure a safe permanent or reversible contact such as various attachment systems for fixation on or in different substrates. In addition to the extensive work on structure and mechanics of rooting systems in land plants [1–7], research has almost exclusively focused on reversible and permanent animal attachment structures. The structure and function of (sub)micrometer scale systems of insects [8–10], spiders [11], tree-frogs [12,13] and geckos [14,15] have been investigated and transferred to some extent into technological applications [16–20]. Animals developed two different ways to adhere reversibly onto a surface [21,22], i.e. hairy or smooth adhesive pads. Pads of e.g. flies, beetles and lizards are covered with deformable "setae" (hair-like structures) which increase the number of contact points with the surface. In contrast smooth adhesive pads, found in cockroaches, bees, grasshoppers and bugs, are soft, deformable structures which secrete a fluid to adhere by wet adhesion. For the hairy pads, it was established that the animal body mass is correlated to the grade of contact splitting in the attachment system [22,23]. Furthermore, sessile marine organisms such as algae or sessile invertebrates exhibit strong permanent adhesion to substrates under severe environmental conditions [24–31]. In particular, the attachment systems of mussels have been studied extensively and were used as concept generators for biomimetic applications [32–34]. A group of attachment structures of comparable efficiency are the holdfasts of climbing plants. However, biomechanical properties and underlying (micro)structures of these organs have not been studied in detail yet.

The life of a plant is a permanent struggle for space, nutrients, and, in particular, for light. Therefore, plants have developed a large variety of climbing strategies enabling them to "get off the ground". Since climbing habits have evolved independently in at least 133 seed plant families [35], climbing can be considered a common and very successful strategy. Different climbing methods can be distinguished in non-self-supporting plants. These methods can be subdivided into four groups [36,37]: (i) climbing by twining plant stems spirally around a support, (ii) climbing with relatively unspecialized structures like hooks or thorns, (iii) climbing using attachment roots that adhere firmly to various substrates, and (iv) climbing with tendrils or other contact-sensitive attachment organs, which may be modified leaves, branches, or inflorescence.

The mechanical properties of stems of climbing plants have been studied in some detail over the last decades [37–43]. These studies prove that different growth forms can be characterized

* Corresponding author. Address: Karlsruher Institut für Technologie (KIT), Institut für Materialforschung und Institut für Zuverlässigkeit von Bauteilen und Systemen, Postfach 3640, 76021 Karlsruhe, Germany. Tel.: +49 7247 824878; fax: +49 7247 822347.
E-mail address: ruth.schwaiger@imf.fzk.de (Ruth Schwaiger).

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by changes in stem mechanics and underlying stem (micro)structure during ontogeny. However, the mechanisms by which plants adhere permanently to organic and inorganic substrates have barely been explored quantitatively yet. Climbing plants permanently attaching to various substrates include root climbers with adventitious roots (e.g. *Hedera helix, Ficus pumila*) or tendril-bearers with attachment pads (e.g. *Parthenocissus* sp., *Pithecoctenium crucigerum*). Morphological, ultra-structural and immunocytochemical studies have led to a qualitative description of the attachment process in tendril-bearing plants [36,44–48]. In the genus *Parthenocissus*, swollen tips develop at the end of the tendrils and form into attachment pads with a size of about 3–5 mm^2 [44,48]. The attachment of *Parthenocissus* sp. is often described as strong in the popular literature but has never been measured precisely [49]. While the anatomy of adventitious roots and the adhesive secretions of ivy rootlets have been studied to some extent [50,51], there is only very limited information on the mechanics. In *F. pumila* – one of the best studied root climbers – the development of attachment roots has been investigated by Groot et al. [52] who could show that the adventitious roots stick together and build clusters which then attach to the substrates.

In this study, the holdfasts of vines that cling directly to surfaces via attachment roots or attachment pads have been mechanically investigated. The attachment strength of attachment pads as well as of attachment roots in their natural habitats and under laboratory conditions was determined using a novel custom-made tensile testing setup. Three different plant species exhibiting different types of attachment structures were studied. The mobile and adaptable tensile tester allows for testing of individual pads as well as of structures consisting of several pads or roots in different environments. Additionally, using the example of *Parthenocissus tricuspidata*, the fresh mass of an individual plant was determined in order to estimate the safety factor of attachment. This factor is an indicator to what extent the load capability of the plant exceeds the working load [53].

2. Experimental details

2.1. Climbing plants

Three different types of climbers with different permanent attachment systems were chosen as model systems: (i) *P. tricuspidata* with attachment pads, (ii) *H. helix* with attachment roots covering the nodes and internodes, (iii) *Campsis radicans* with attachment roots clustered at the nodes.

Parthenocissus tricuspidata is a tendril-bearer within the grape family Vitaceae. It is a vine native to eastern Asia. Its tendrils develop swollen tips that form into attachment pads which then adhere to the substrate and enable the plant to climb up rocks, trees, and walls. The investigated individuals belong to the cultivar *P. tricuspidata* "Veitchii". Samples were taken from two well-established plants of approximately 3 m height on outdoor walls facing east at the Botanic Garden at the University of Freiburg. The tested attachment pads were about one year old, fully lignified and grown on a wall with plaster (Fig. 1a).

Hedera helix is an evergreen woody root climber of the family Araliaceae. English ivy is native to most of Europe, the west coast of South America, southwest Asia and Australia. The English ivy climbs with adventitious attachment roots which are mostly double rowed and distributed over the whole internode and node. The tested individuals were grown outdoors in the Botanic Garden at the University of Freiburg. Samples were approximately 2 cm long internodial pieces of the plant growing on bark of *Celtis occidentalis* (Fig. 1b).

The trumpet vine (*C. radicans*) is a woody root climber of the family Bignoniaceae, native to woodlands of the southeastern USA. Their attachment roots are located exclusively at the nodes. Every root has dense root hairs which build up clusters by interlocking (Fig. 1c). Ten mature individuals of about 1.20 m height were cultivated in a green house of the Botanic Garden at the University of Freiburg. Samples were grown on 5 × 10 cm birch wood plates as climbing substrates.

2.2. Experimental setup

A mobile and adaptable tensile testing machine was developed and built in-house in order to test individual attachment systems under natural growth conditions as well as in the lab (Fig. 2). In order to avoid artifacts due to drying out of the samples, the attachment structures need to be tested in situ. The main components of the tensile tester are a load sensor and a displacement sensor positioned on a linear unit with a spindle drive. The main advantages of linear units with spindle drives are their very high load capacity and their smooth movement. A linear unit RK Compact (RK Rose + Krieger GmbH, Minden, Germany), which converts a rotating movement of the spindle into a linear movement of the guide table, was selected. Tension–compression membrane load cells with load ranges of 0–20 and 0–200 N were used. The displacement sensor is a potentiometric displacement transducer (range 50 mm, Burster Präzisionsmesstechnik GmbH & Co KG, Gernsbach, Germany). Load and displacement data are directly transferred to a portable computer via a USB sensor interface. The horizontal movement on the linear unit is conducted by an electric motor to ensure a consistent and smooth traction. In order to achieve reproducible measurements, the force to be measured must be applied axially, i.e. parallel to the tendril axis. Therefore, the described measuring unit is placed on a ball-ended very stable tripod (G2220, Gitzo, Rungis Cedex, France). This free rotating ball

Fig. 1. Climbing plants with permanent attachment structures. (a) *Parthenocissus tricuspidata*: main axis bearing tendrils with attachment pads. (b) *Hedera helix*: internodal attachment roots. (c) *Campsis radicans*: nodal attachment roots.

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