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# **Mechanics and morphology of permanent attachment systems in plants**

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## Abstract

Permanent attachment pads of climbing plants are an example of highly efficient attachment structures, which have been evolved, tested and optimized in the course of evolution. However, information about the attachment mechanisms is still scarce, although the excellent mechanical performance of attachment structures has been recognized. In this study, the morphology and the biomechanics of attachment pads of Boston Ivy (*Parthenocissus tricuspidata*) as well as the interface between the pad and different substrates were investigated. The self-clinging liana *P. tricuspidata* develops swollen tips at the end of its tendrils which form into attachment pads. Attached and non-attached structures were analyzed using microscopical and mechanical testing methods. The overall strength of the interface was studied using tensile tests on a large number of individual pads attached to different substrates. On the micrometer-scale, the mechanical properties of the constituent materials were studied using nanoindentation.

Ontogenetic variations in the morphology of attached and non-attached structures were observed. Cell size, cell orientation and grade of lignification vary over the pad cross-section normal to the interface. Furthermore, cell size, cell wall thickness as well as cell orientation show variations in the plane of the interfacial region. The cells in the edge regions appear to secrete a strong adhesive fluid. The morphological variations are related to changes in mechanical properties. For example, the region close to the pad edge is up to four times stiffer than the regions closer the pad center.

A single lignified pad withstands normal stresses at the interface of up to 4 MPa while failure never occurred only at the interface. Four different failure modes were observed: failure of the substrate, internal failure of the attachment pad, a combination of the two modes or in case of non-porous materials mixed failure of plant components and interface. The attachment strength of young pads has been found to be significantly smaller than the attachment strength of older, lignified pads. It was on average only 28% of the value found for the older pads. The attachment process can be described at least as a two step process with a pre-attachment and a final attachment. Microscopical investigations show a perfect form closure between pad and substrate. Overall, attachment structures of climbers can be considered as a composite material and these natural interfaces are promising models for new technological concepts.



## Kurzzusammenfassung

Permanente Haftscheiben bei Kletterpflanzen stellen ein Beispiel für hoch-effiziente pflanzliche Anhaftstrukturen dar, die die Natur im Laufe der Evolution entwickelt, getestet und optimiert hat. Obgleich die exzellente mechanische Leistungsfähigkeit biologischer „Werkstoffverbunde“ bekannt ist, sind die zugrunde liegenden Strukturen der Grenzflächen, wie interne „Verschweißungen“ und „verklebte“ Grenzschichten, noch wenig beschrieben. Ziel dieser Arbeit ist es, die (Mikro)-Mechanik und Funktionsmorphologie permanenter Haftscheiben des Wilden Weins (*Parthenocissus tricuspidata*) sowie die Materialgrenzflächen zwischen der Haftscheibe und verschiedenen Substraten in einem interdisziplinären Ansatz zu untersuchen. Angehaftete und nicht angehaftete Strukturen wurden morphologisch und mechanisch charakterisiert. Die Haftkraft der Gesamtstrukturen wurde mit Hilfe von Zugversuchen bestimmt und die mechanischen Eigenschaften der einzelnen Gewebe durch Nanoindentation.

Während der Entwicklung der Haftstrukturen werden verschiedene typische Stadien durchlaufen. Voll ausdifferenzierte Haftscheiben weisen sowohl über den Querschnitt als auch über die Kontaktfläche diverse Gradienten auf. Zellgröße, Zellorientierung und Grad der Lignifizierung variieren über den Querschnitt. Die Kontaktfläche der Haftscheiben weist ebenfalls Variationen der Zellgröße, der Zellorientierung und der Zellwanddicke auf. Morphologisch kann ein innerer und ein äußerer Bereich auf der Kontaktfläche unterschieden werden, wobei in der äußeren Region ein Haftsekret sezerniert wird. Die morphologischen Änderungen resultieren in Änderungen der mechanischen Eigenschaften. Der äußere Bereich der Kontaktfläche ist zum Beispiel bis zu vier Mal so steif wie die inneren Regionen.

Zugversuche haben gezeigt, dass eine Haftscheibe Spannungen von bis zu 4 MPa standhält, wobei im Fall des Versagens die Haftscheibe niemals komplett vom Substrat getrennt werden konnte. Es traten vier verschiedene Versagensmodi auf: Versagen des Substrates, internes Versagen der Haftscheibe, teilweises Versagen des Substrates und der Haftscheibe, und im Fall von glatten Oberflächen ein teilweises Versagen von Komponenten der Haftscheibe. Die Haftkraft junger Haftscheiben ist signifikant geringer als die von älteren, lignifizierten Haftscheiben. Sie betrug im Mittel nur 28% des Wertes der für lignifizierte erreicht wurde. Die Anhaftung kann daher mindestens als 2-stufiger Prozess mit einer Voranhaftung und einer finalen Anhaftung verstanden werden. Untersuchungen der Materialgrenzfläche zeigen einen perfekten Formschluss zwischen der Haftscheibe und dem Substrat.





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