Criterion of detachment for grip-and-release devices with slanted multi-beam structure using Ti–Ni wire

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Abstract. A multi-beam structure using Ti–Ni wire to grip rough surfaces and control detachment was manufactured. The grip-and-release mechanism of the structure was investigated. The experimental results were analyzed with a model assuming beam theory and using a fracture criterion at the adhered interface. The fracture criterion of the adhesion interface is suggested to depend on the shear stress.

1. Introduction

Geckos can grip rough surface with adhesion force and move quickly with their foot hairs, which are called setae and spatulæ [1]. These hairs generate an adhesion force, and the grip-and-release is controlled by a tangential force [2]. These hairs inspired the development of a multi-beam structure. The structure consists of many beams with adhesive applied to the tips of the beams, as shown in figure 1. The structure grips a rough surface with the adhesion force and controls detachment with the tangential force. The adhesion devices can be applied to non-magnetic materials and in a vacuum. Clarifying the detachment criterion is important for the design of the adhesion devices. Although Wang et al. investigated the detachment mechanism of the multi-beam structure [3], their beams were vertical and too hard to absorb the surface roughness. In the present study, soft and slanted beams were considered. Ti–Ni superelastic wires were used for the beams. The mechanism of the detachment was experimentally investigated and analyzed according to beam theory.

Figure 1. Model of multi-beam structure inspired from gecko foot hairs.
2. Multi-beam structure
Figure 2 shows the construction of the multi-beam structure used in this study. The beams comprise Ti–Ni super-elastic wires with diameters of 0.10 mm. Ten wires are fixed to 0.2 mm thick copper sheets and 0.1 mm thick tin foil by brazing. The tips of the beams are polished at 45°.

![Figure 2. Construction of multi-beam structure.](image)

3. Experiment to investigate detachment mechanism

3.1. Model of detachment mechanism
The structure adheres to a surface at the beam tips and is dragged, as shown in figure 3. The detachment mechanism of the structure was assumed to be a superposition of the mechanism for a single beam. The normal load \( F_n \) and tangential force \( F_t \) are applied to the tips of the structure side for each beam. \( F_n \) corresponds to the supported weight. The mechanism of the beam was considered using beam theory and the fracture criterion of the adhesion interface [4]. The maximum normal stress \( \sigma_{\text{max}} \) is taken from beam theory and expressed in equation (1); it is shown in figure 4 with various values of \( F_t \), where \( S \) is the contact area, \( l \) is the length of the beams, \( \theta \) is the angle of the beams, and \( Z \) is the section modulus. When \( \sigma_{\text{max}} \) is greater than the critical value \( \sigma_{\text{cr}} \), the adhesion interface is broken, and the beam detaches from the surface. \( \sigma_{\text{cr}} \) was assumed to be constant and unique at the interface. By controlling \( F_t \), \( \sigma_{\text{max}} \) can be controlled. In other words, the detachment from the surface can be controlled. The fracture criterion is defined as \( \sigma_{\text{cr}} \) and is expressed in equation (2). The detachment criterion of a single beam is defined as \( F_n \) and \( F_t \) when detachment occurs and is expressed in equation (3); it is shown in figure 5.

\[
\sigma_{\text{max}} = \frac{F_n}{S} \left[ Fr\cos \theta - F_t \sin \theta \right] \frac{1}{2Z} \\
\sigma_{\text{max}} > \sigma_{\text{cr}} \quad (1)
\]

\[
\sigma_{\text{cr}} = S \sigma_{\text{c}} + \frac{q l \cos \theta - 2 \frac{l \sin \theta}{Z} \left( q l \cos \theta - 2 \frac{l \sin \theta}{Z} \right)}{4 \frac{l \sin \theta \cos \theta}{Z}} \\
F_n = \frac{S \sigma_{\text{cr}} + \frac{q l \sin \theta}{Z} \left( q l \cos \theta - 2 \frac{l \sin \theta}{Z} \right)}{4 \frac{l \sin \theta \cos \theta}{Z}} \quad (3)
\]

![Figure 3. How multi-beam structure grips surface.](image)

![Figure 4. Normal stress distribution at adhesion interface.](image)
3.2. Experimental system and process

To investigate the detachment criterion of the structure, the adhesion force between the beam tips and urethane sheet acting as the adhesive was measured. Figure 6 and table 1 show the experimental setup for the adhesion force measurements. A 0.5 mm thick urethane sheet is placed on the tilting surface as the adhesive. The structure was moved vertically by a motorized stage. The maximum adhesion force $F$ was recorded by an electric balance. The measurement was carried out for various tilt angles $\phi$. The tilt angle $\phi$ corresponds to the angle of resultant force of $F_t$ and $F_n$. $F_t$ and $F_n$ were evaluated from $F$ and are expressed in equation (4).

$$\begin{cases} F_t = F \cos \phi \\ F_n = F \sin \phi \end{cases} \quad (4)$$

The experiment was carried out according to the following process. (1) The structure was moved vertically at 1 $\mu$m/sec and adhered to the surface. (2) After contact, the structure was removed from the surface vertically at 1 $\mu$m/sec. The detachment criterion was evaluated using $F$ and $\phi$. The experiments were carried out from $\phi = 25^\circ$ to $\phi = 65^\circ$ at intervals of $5^\circ$.

![Figure 5. Detachment criterion of single beam.](image)

![Figure 6. Measurement of adhesion force.](image)

### Table 1. Experimental setup.

| Name                      | Explanation                       |
|---------------------------|-----------------------------------|
| (a) KZL060(Suruga seiki)  | Motorized stage, resolution: 1$\mu$m |
| (b) B43-60N(Suruga seiki) | Manual rotation stage, resolution: 0.2$^\circ$ |
| (c) AY-220(SHIMADZU)     | Electric balance, resolution: 0.1mg |
| (d) CT-05W-500(Exseal corp.) | Adhesives, urethane sheet 0.5mm thick |
4. Results and discussion
Figure 7 shows the experimental results. The plotted points represent the maximum adhesion force at each $\varphi$. Figure 8 shows the detachment criterion. The plotted points represent the experimental detachment criterion evaluated from the experimental results and equation (4). The theoretical detachment criteria calculated from equations (1) and (2) are also plotted in figure 8; the solid and broken lines correspond to $\sigma_{cs} = 100$ kPa and $\sigma_{cs} = 10$ kPa, respectively. The results from equations (1) and (2) showed poor agreement with the experimental results. Figure 9 shows $\sigma_{\max}$ calculated from the results using equation (2). The disagreement can be observed around $\varphi = 45^\circ = \theta$. In the model, because the normal stress distribution was uniform when $\varphi = \theta$, the structure hardly detached from the surface and could support heavier weights than when $\varphi > \theta$ and $\varphi < \theta$. Assuming that the shear stress distribution is uniform, the shear stress $\tau_{\text{ave}}$ at the interface can be expressed as

$$\tau_{\text{ave}} = \frac{F_{t}}{S} = \frac{F \cos \varphi}{S}. \quad (5)$$

Figure 10 shows the relationship between $\tau_{\text{ave}}$ and $\varphi$. Figures 9 and 10 indicate that $\sigma_{\max}$ decreases as $\tau_{\text{ave}}$ increases; in other words, $\sigma_{cs}$ decreases when shear stress is applied at the adhesion interface. For the case $\varphi = \theta$, the more a beam becomes slanted, the more $\sigma_{cs}$ decreases. Thus, the fracture criterion needs to be modified for design of the structure.

![Figure 7. Maximum adhesion force at various tilt angles for tables.](image1)

![Figure 8. Experimental and theoretical detachment criteria.](image2)
5. Conclusion
A slanted multi-beam structure using Ti–Ni wire was fabricated. The structure grips rough surfaces with adhesion force and controls detachment from the surface. The maximum adhesion force between the structure and a urethane sheet acting as the adhesives was measured. The detachment mechanism of the structure was investigated and analyzed according to beam theory and the fracture criterion of the adhesion interface. The fracture criterion is suggested to be a function of the shear stress.

References
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