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Impact Behaviour of the Japanese Sword

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The Japanese sword is a weapon peculiar to Japan. The present study is concerned with the joint between *tohshin* (blade) and *tsuka* (hilt) of the Japanese sword. Only one *mekugi-take* (retaining peg made of bamboo) with about 5mm in diameter holds the tang in the hilt. However a slender *mekugi* might not be broken, even in the case of violent sword-fighting. This fact has been historically demonstrated in many battles by Japanese swords. In this study it is examined theoretically and experimentally from the viewpoint of impact engineering why a *mekugi* used in *Tachi* and *Katana* may not be broken. As a result, it is found that such a strong force as breaking a *mekugi-take* does not act on it, because of the location of *mekugi-ana* (a hole for *mekugi*) in the tang, which has been made in the Japanese sword by following the traditional code of sword-smiths.

Key words: impact force, impact response, Japanese sword, Tachi, joint of blade and hilt, mekugi-ana.

1. Introduction

The Japanese sword is a weapon peculiar to Japan. What we call the *Nippontoh* (the Japanese sword) includes various forms of blades such as *Ken*, *Naginata* and *Yari* in addition to the more common *Tachi*, *Katana*, *Wakizashi* and *Tantoh*. These swords except *Ken* and *Yari* are single-edged weapons for slashing, cutting and stabbing. The Japanese sword must fulfill the three functional requirements of not breaking, not bending and cutting well, as well as being an aesthetic work of craftsmanship. The s*ugata* and *sori* (graceful shape and curve), the changes in the *jihada* (blade surface) and *hamon* (temper patterns) of the Japanese sword make it a work of art. In the past, the Japanese sword was valued for its utility as a weapon, but nowadays it is an artwork of typical traditional crafts in Japan [1–5].

The Japanese sword is interesting not only from the viewpoint of traditional crafts of arts, but also from the aspect of modern science and technology because the way of making and its functionality in weapon are really consistent with science [6–8]. The present study is concerned with the joint between *tohshin* (blade) and *tsuka* (hilt) of the sword. Only one *mekugi-take* (retaining peg made of bamboo) with about 5 mm in diameter holds the tang in the hilt. However the slender *mekugi* might not be broken, even in the case of severe sword-fighting. This fact has been historically demonstrated in many battles by Japanese swords.

So far we have examined it with models of the Japanese sword [9, 10]. In this study, it is investigated with an actual *Tachi* theoretically and experimentally from the viewpoint of impact engineering why a *mekugi* used in Japanese swords may not be broken even in the violent sword-fighting.

2. Tachi and Katana in the Japanese sword

There are *Tachi*, *Katana*, *Wakizashi*, *Tantoh*, *Ken*, *Naginata* and *Yari* in the Japanese sword. Classification of the blade in the Japanese sword is depicted in Fig. 1. From the Heian period (11th century) through the early part of the Muromachi period (14th century), *Tachi* was worn slung from the waist with edge-side downwards. *Tachi* usually have a high curvature (*sori*), and the length of blade is more than 60.6 cm (2 *syaku*), usually 65–80 cm. Here, *syaku* is an old Japanese unit to measure length. *Katana* came into widespread use in the middle of the Muromachi period (15th century) and was in use until the very end of the Edo period (19th century). *Katana* is 60.6 cm long or more, but usually somewhat shorter than *Tachi*. In contrast to *Tachi*, *Katana* is worn thrust edge upwards through the belt. Swords in length between 30.3 cm (1 *syaku*) and

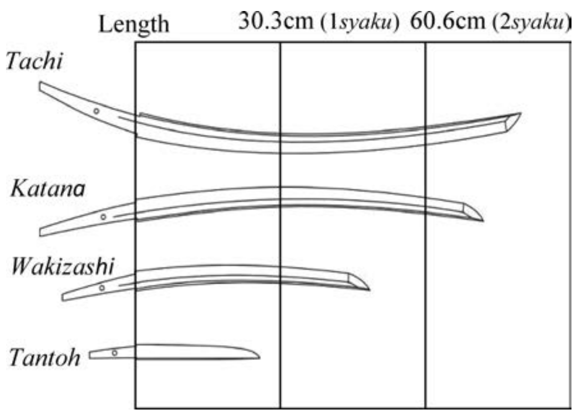

Fig. 1. Classification of the Japanese sword.

60.6 cm are called *Wakizashi*, and was worn on the waist like *Katana*. During the Edo period, a *wakizashi* was worn with a *katana* as a *dai-sho* (a pair of large and small swords). Swords shorter than 30.3 cm are called *Tantoh*.

It is said that the curved and ridged blade familiar to us as *shinogi-zukuri tachi* came into existence in the middle of the Heian period (11th century). The cross section of *shinogi-zukuri* blade is illustrated in Fig. 2. A bar of core steel (*shingane*) with low carbon content wrapped by hard skin steel (*kawagane* and *hagane*) with high carbon content goes through the forging process. This process is called *tsukurikomi*, and the combination of two or three kinds of different steels with different carbon content produces the characteristic of the Japanese sword. Thus such a combination of different kinds of steel results in the nonuniform distribution of carbon in the cross section and this duplex structure gives the sword high strength, toughness and ductility. After rough shaping, the sword is transferred to the final process of quenching or hardening (*yakiire*). Before *yakiire*, a kind of clay (*yakiba-tsuchi*) is coated on the surface of the blade to control the heat transfer intensity. The coated clay is thick on the ridge while thin on the edge part. During the quenching process, the regions near the cutting edge are transformed from unstable austenite to martensite, while other regions remain pearlite and ferrite structure. Consequently, temper patterns (*hamon*) appear at the border of those parts, and the graceful curved shape peculiar to the Japanese sword is generated at the same time.

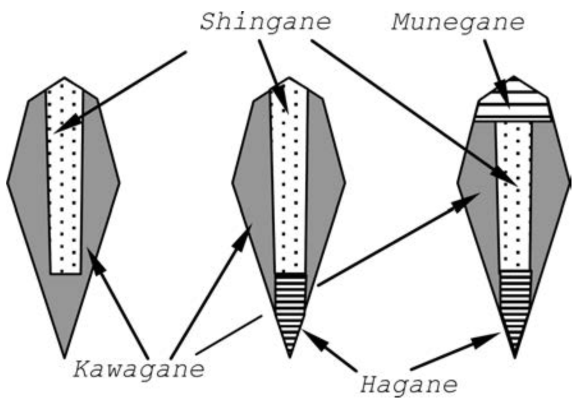

FIG. 2. Tukurikomi: a) *Koubuse*, b) *Honsannmai*, c) *Shihouzume*.

The traditional mounting of the Japanese sword for practical use is called *koshirae*. *Koshirae* consist of a lacquered wooden scabbard, a wrapped and braided hilt, sword guard and other decorative metal fittings. Figure 3 shows a dismantled Japanese sword of *koshirae*. Only one *mekugi-take* (retaining peg made of bamboo) with about 5 mm in diameter holds the tang in the hilt, therefore the Japanese sword with *koshirae* is easily dismantled by merely pulled out

FIG. 3. Parts of the Japanese sword.

a *mekugi-take*. Considering that the swords were used in the battle of violent sword-fighting, this simply traditional technique is astonishing from the viewpoint of assembly technology.

3. Impact behaviour of Tachi blade

Figure 4 shows a *tachi* used in the present study: a) a *tachi* with *koshirae*, b) dismantled parts, and c) a *tachi* blade. The blade is 700 mm (2*syaku* 3*zunn*) long with 19.5 mm (7*bu*) of curvature (*sori*). For the sake of safety in experiments, the sharp edge of the blade is dulled such as the thickness of edge end approximately 0.2 mm. Main dimensions of the *tachi* blade are shown in Fig. 5.

FIG. 4. *Tachi* used for impact experiment and numerical simulation.

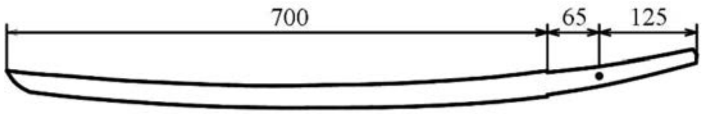

FIG. 5. Dimensions of *Tachi* blade.

In the actual sword-fighting the sword is supposed to be subjected to various impact forces at different positions of the blade. The schematic of experiments performed in this study is shown in Fig. 6. A *tachi* blade hung vertically by cotton string from a frame is subjected to an impact force by a copper striking bar (1000 mm in length and 10 mm in diameter). The impact force incident to the sword and the variation of displacement with time at each location along the axis of a blade are measured.

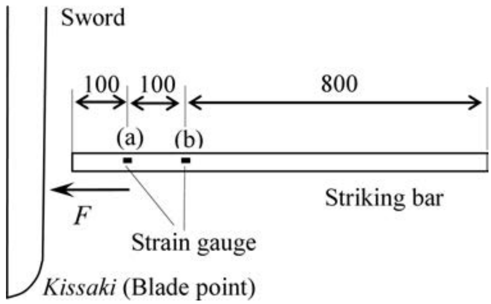

FIG. 6. *Tachi* blade subjected to impact force by a striking bar.

The incident forces measured in experiments are shown in Fig. 7 by solid and broken curves, which were obtained by impacting the striker with an impact velocity of 2.6 m/s to the position of 100 mm and 350 mm from *kissaki* (blade

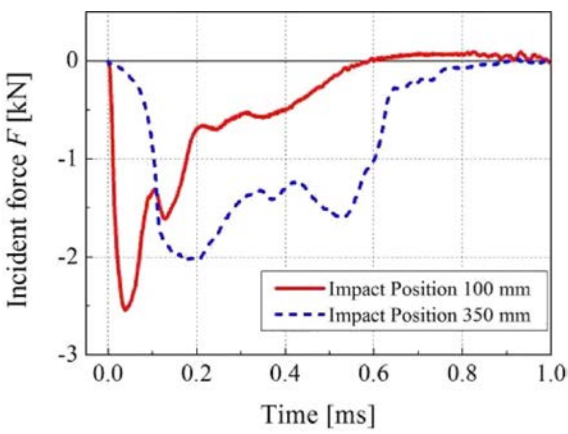

FIG. 7. Incident forces into *Tachi* blade.

point) of the blade, respectively. The diagrams of force vs. time were given by a measuring method using two strain gauges, which makes it possible to eliminate the effect of reflect waves from the opposite free end of a striker [11]. The waves of two incident forces are different from each other due to the impacted position.

On the other hand, the fluctuation of displacement with time at each location along the axis of the blade was measured by making use of a CCD laser displacement sensor (KEYENCE, LK-G155). Figure 8a and b show the variations

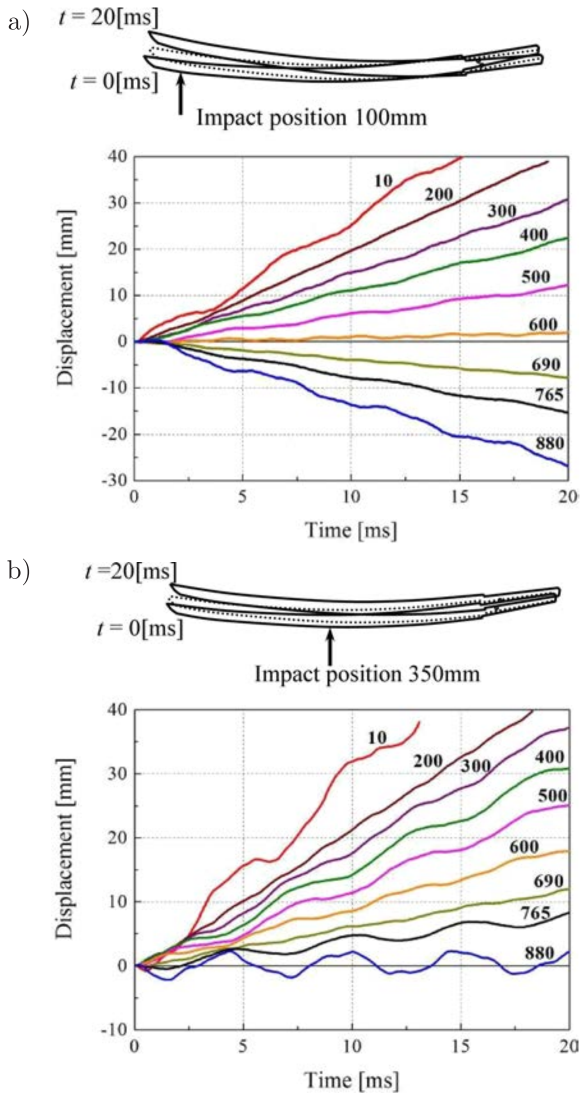

Fig. 8. Variation of displacement with time at each location: a) impact position of 100 mm from *Kissaki*, b) impact position of 350 mm from *Kissaki*.

of the displacement with time, including the rigid body displacement, when the impact forces shown in Fig. 7 were applied on each position of 100 mm and 350 mm from *kissaki* of the blade, respectively. The numerical value on each curve indicates a distance from *kissaki*. In addition the whole movement of the blade is illustrated above the figures.

By taking off the rigid body displacements from those displacement curves, the oscillation curves were obtained. Figure 9a and b show the oscillation of the displacement at the location of 10 mm, 765 mm, and 880 mm from *kissaki*, which correspond to the vicinity of *kissaki*, the location of *mekugi-ana*, and the vicinity of *nakago-jiri* (the end of the tang), respectively. In both cases of the impacted positions of 100 mm and 350 mm, the displacement amplitude at the

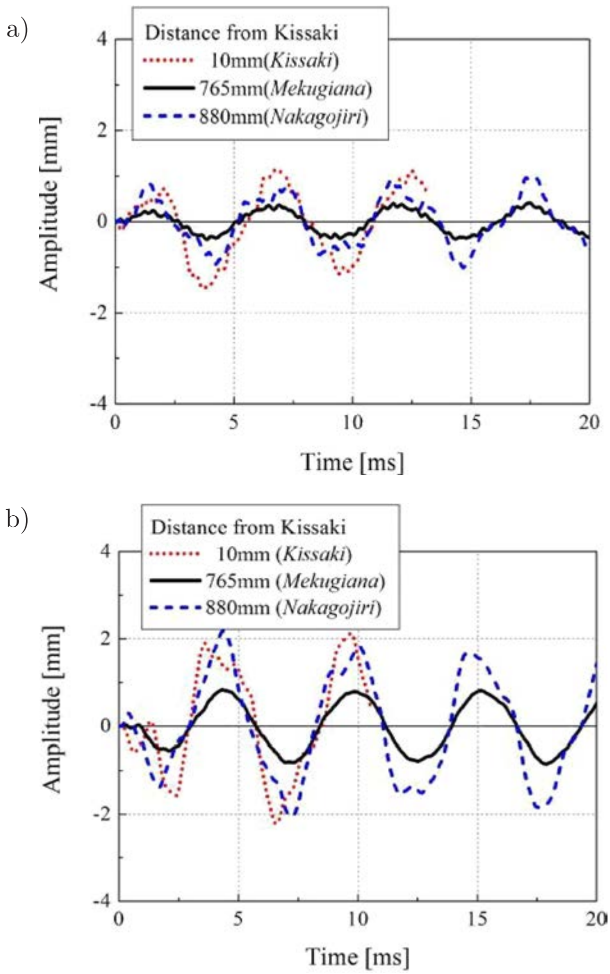

Fig. 9. Oscillation of displacement at each position: a) impact position of 100 mm from *Kissaki*, b) impact position of 350 mm from *Kissaki*.

location of *mekugi-ana* becomes small compared to one at other locations. The amplitude at each location of the blade is presented in Fig. 10 for both cases of the impacted positions of 100 mm and 350 mm. It can be seen that the distribution of the displacement amplitude along the axis of a blade is similar in spite of the differences of the impact position and the incident force. The amplitude at the vicinity of *kissaki* and *nakago-jiri* is large, but it becomes comparatively small at the neighborhood of *machi* (notch on the boundary between the blade and the tang).

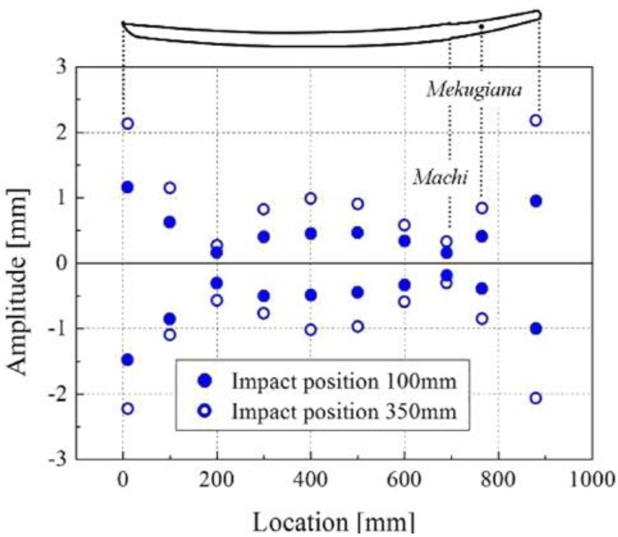

Fig. 10. Distribution of amplitudes for impact positions of 100 mm and 350 mm from *Kissaki*.

Numerical simulations were also carried out, based on the incident forces given in Fig. 7. As was stated previously, the structure of a sword blade is heterogeneous and composite. However, the velocity of elastic stress waves is determined only by elastic modulus E, density ρ and Poisson's ratio ν, and the difference in these elastic values of ferric materials is small. Therefore, a series of numerical simulations for a sword model made of a single material with $E =$ 206 GPa, $\rho = 7.85 \cdot 10^3$ kg/m^3 and $\nu = 0.29$, were carried out by using a code of LS-DYNA.

A three-dimensional finite element mesh division of the sword is represented in Fig. 11, where the division is made for a half-part in the width direction due to symmetry. Figures 11a and 11b respectively denote the whole region and the enlarged part near the blade tip (*Kissaki*) and the tang (*Nakago*). The total number of the elements used in the model is 8,916, and that of the nodes is 12,600.

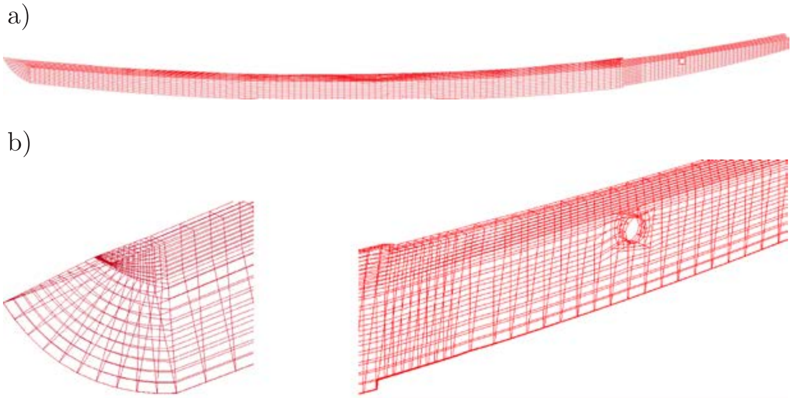

Fig. 11. Finite element division of the sword: a) whole region, b) near the blade tip and *Mekugi-ana* in the tang.

Figure 12 shows the comparison between the experimental results (circles) and the numerical results (curves) concerning the displacement amplitude at each location of a *tachi* blade. The numerical results show good agreement with the experimental ones.

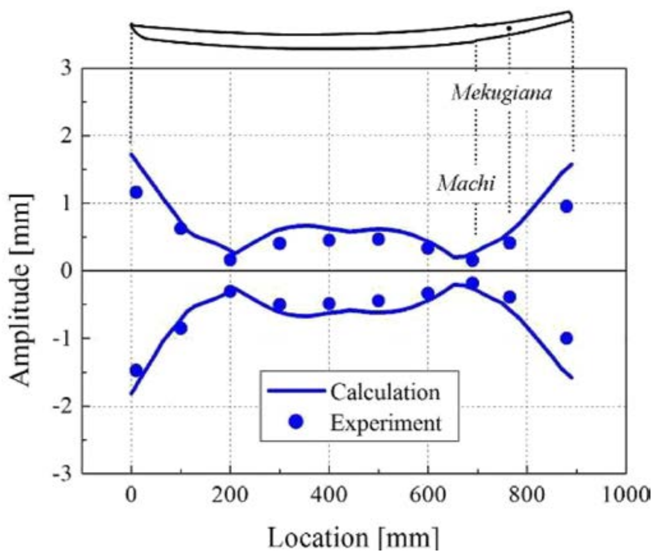

Fig. 12. Comparison between the measured and simulated amplitudes (impact position of 100 mm).

If a *mekugi-take* is not easily broken even in the severe sword-fighting, it seems reasonable that the amplitude would have a certain minimum value just at the location of *mekugi-ana*. However, as seen in Figs. 10 and 12, the minimum amplitude is at the neighborhood of *machi*. This may be by reason of only a blade, that is, a *tachi* without *koshirae*. Therefore in order to inspect the effect of *koshirae* such as *tsuka* (hilt), *tsuba* (sword guard) and other metal fittings on the displacement amplitudes, a *tachi* with *koshirae* was also examined in the same manner.

4. Tachi with koshirae

Figure 13 shows a *tachi* with *koshirae*, which is the traditional mounting of the Japanese sword for practical use, and consist of a lacquered wooden scabbard, a wrapped and braided hilt, a sword guard and other metal fittings such as a *habaki* and a pair of *seppa*.

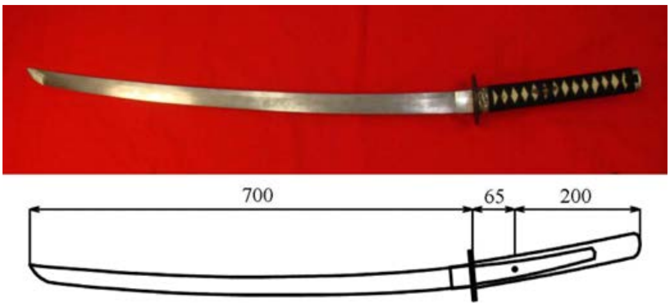

Fig. 13. *Tachi* with *koshirae*, and dimensions.

Figure 14a shows the variation of the displacement with time at each location of a *tachi* with *koshirae*, which is subjected to an impact force at the position of 10 cm from *kissaki* by a striker bar. The numerical value on each curve indicates a distance from *kissaki*. Then by subtracting the rigid body displacement from those displacement curves, the oscillation curves at the locations of *kissaki*, *mekugiana* and *tsuka-gashira* (the end of the hilt) of the *tachi* with *koshirae* were obtained as shown in Fig. 14b.

Based on those results, the distribution of the amplitude at each location of the t*achi* with *koshirae* was obtained as shown by solid circles in Fig. 15. In order to compare the case of the *tachi* blade to the case of the *tachi* with *koshirae*, the results on the blade presented in Fig. 10 are plotted by open circles in addition. It can be seen that the displacement amplitude for the *tachi* with *koshirae* becomes to the minimum just at the location of a *mekugi-ana*, while the minimum amplitude for the case of only a blade stands at the vicinity of *machi*.

The position of a *mekugi-ana* (a hole for *mekugi*) has been determined by following the individual traditional code of sword-smiths in the Gokaden (the five traditions of sword making) and their schools. It is found from the present study, in which a Bizen style blade was employed, that such strong forces as

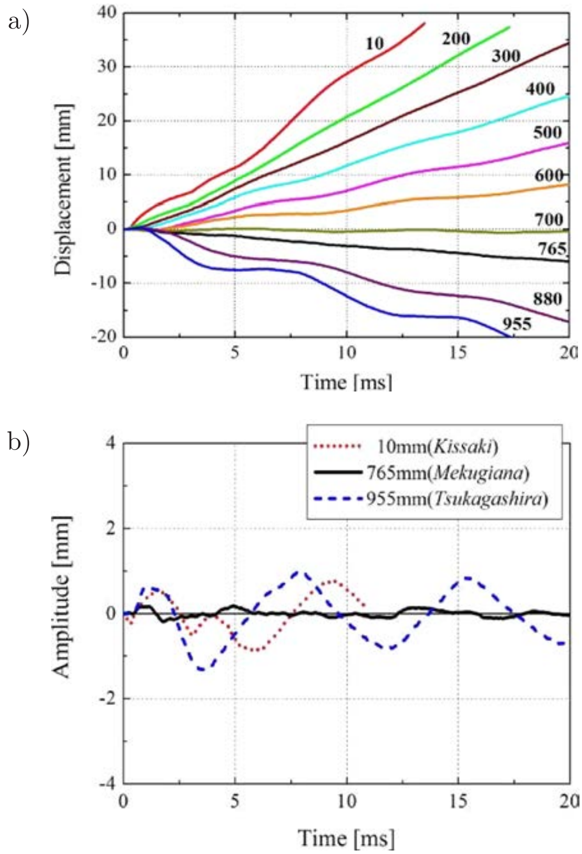

FIG. 14. Impact responses of *Tachi* with *koshirae*: a) variation of displacement with time at each location, b) oscillation of displacement.

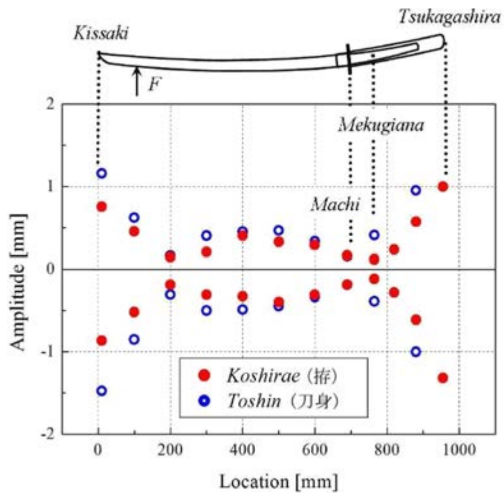

FIG. 15. Comparison of amplitudes for *Toshin* (*tachi* blade) and *Tachi* with *koshirae*.

breaking a *mekugi-take* would not act on it in the Japanese sword made by the traditional code of sword-smiths.

5. Concluding remarks

In this study it is examined with an actual *tachi* from the viewpoint of impact engineering why a *mekugi* used in Japanese swords may not be broken even in the violent sword-fighting. As a result, it is found in the *tachi* with *koshirae* (practical mounting) that such a strong force as breaking a *mekugi-take* would not act on it, by reason of the location of *mekugi-ana* (a hole for *mekugi*) in the tang, which has been made in the Japanese sword by following the traditional code of sword-smiths.

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