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DUELLING TIMBER FLOATS OF JAPAN'S FUSHIKI HIKIYAMA FESTIVAL

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ABSTRACT: Each spring the town of Fushiki in Japan's Toyama prefecture plays host to a unique cultural event – the Fushiki Hikiyama festival. Timber engineers will find interest in the culmination of the festival: a series of duels in which predominantly wooden festival floats armed with what can only be described as battering-rams, are brought together at speed in a series of spectacular collisions. The authors were brought together by the Civic Cultural Heritage Network Tottori, a Japanese cultural organisation, to carry out a preliminary investigation of the festival floats; both for engineering and cultural interest, and as a possible exemplar of the behaviour of traditionally carpentered structures subject to high dynamic loads. The second, third and fourth authors travelled to Fushiki to observe the May 2016 festival and to carry out an after-the-battle inspection of one of these unique duelling floats. High-speed and high-resolution video was used for digital image correlation measurement of the collisions, to quantify the magnitude of the impact.

KEYWORDS: Japan, heritage, dynamics, impact, tradition, carpentry connection

1 INTRODUCTION

The tradition of wood-framed festival floats adorned with decoration is widespread in Toyama prefecture and in other parts of Japan [1], but the combative aspect of the Fushiki Hikiyama is rather less common. The authors are led to believe that this is now the last remaining festival of its type in Japan.

The four Fushiki Hikiyama floats, between 8 and 10 tonnes in weight, are understood to have originated following the introduction of Mikurumayama floats to the region in the nearby city of Takoaka. The earliest of the Fushiki floats was constructed in 1820 and the most recent in 1892. One float, originally constructed in 1864 was reconstructed in 2015 following a severe fire.

The Fushiki Hikiyama floats adopt many of the aesthetic conventions of the ornamental Takoaka Mikurumayama, but combine these with a local tradition of naval combat demonstrations. In this sense, the duelling floats can be thought of as part chariot, part warship, and the details of their construction appear to owe as much to traditional shipbuilding as to the carpentry of buildings.

Figure 1: *One of the floats on public display – the adornments are changed before the duel, but the roundwood ram assembly at either end can be seen.*

The early part of the festival includes exhibition of the

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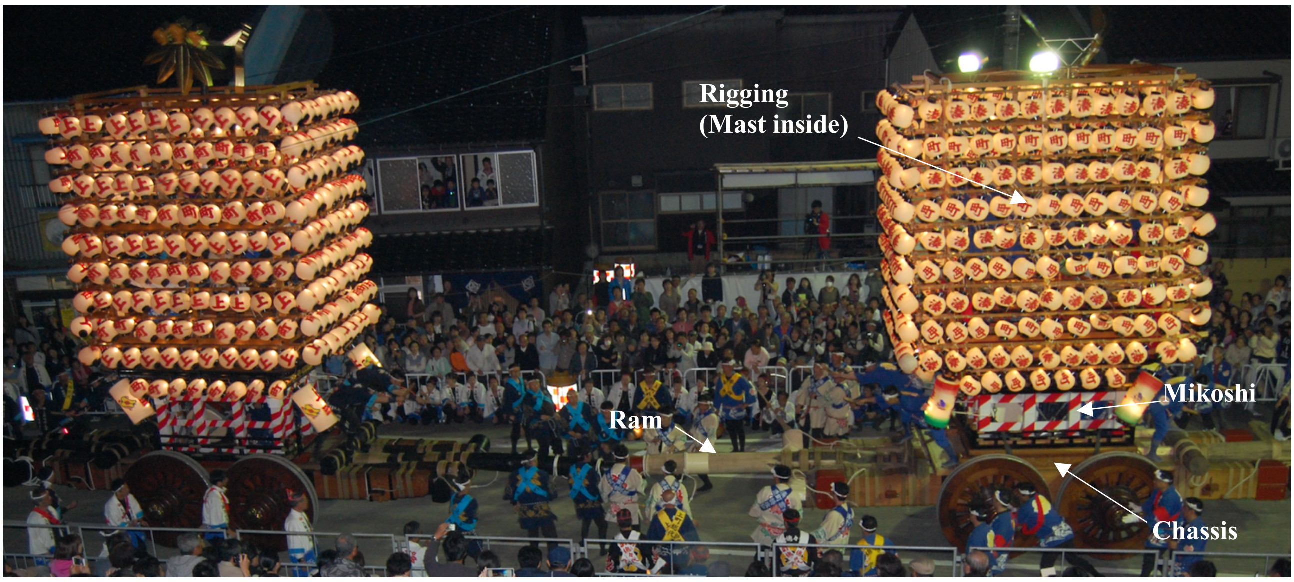

Figure 2: *Two floats near the moment of impact during the duel, showing named parts of the float*

floats, as shown in Figure 1. After exhibition, the adornments around the central 'mast' are changed to an array of lanterns around a timber frame, seen on two competing floats in Figure 2.

Even without the duelling element, Japanese wooden festival floats require wooden components to resist large moving forces. Yasui et al. [2] study the static and dynamic structural behaviour of a non-duelling float from Shiga prefecture, including an analysis of the axle structure. The collisions in the duels of the Fushiki Hikyama, however, introduce high dynamic loads comparable to or exceeding those studied in seismic and impact engineering [3,4].

2 DESCRIPTION OF THE FLOATS

The structure of the floats can be divided into four principal sub-structures, labelled in Figure 2:

- the ram-assembly,
- the chassis,
- the Mikoshi, and
- the mast with its 'rigging' and curtains of lanterns.

Although disassembled for maintenance after each festival, the chassis and mast are reused each year. The chassis is composed of very large, planed, carpentered, rectangular sections while the Mikoshi is constructed in a similar manner but with smaller sections. The Mikoshi could broadly be characterised as a post and beam construction. There is no diagonalization or substantial haunching of the timber in the chassis or Mikoshi.

The masts would have originally been round-wood timber, but today six of the seven masts are steel circular hollow sections. The mast is effectively clamped at the base and part-height by the chassis and Mikoshi respectively, with a substantial length free to sway above this. The mast thus has the potential to act as an inverted pendulum, attached by the rigging to the curtains of 365 lanterns that are themselves free to swing. Although very low in mass, the surface area of the lanterns is considerable, meaning that the whipping of the mast is likely to encounter significant air resistance. The ram-assembly comprises an oak round-wood primary ram and twin secondary rams that are connected directly to the leading transverse beam of the chassis, and also with hemp rope binding directly to the longitudinal chassis beams and via the transverse ram-assembly beams. The ram substructure therefore has potential to dissipate energy through frictional contact of the ram-assembly timbers and the hemp rope binding.

Other than the masts, all floats are predominantly wooden structures. However, for at least the last 40 years, significant amounts of steel have been incorporated in various ways:

- Large steel plates and brackets are used to connect the primary and secondary rams to the leading lower transverse beam of the chassis.
- The end of the ram is confined by a steel hoop.
- The axles are fixed stubs of lubricated steel which the wheels rotate around. The wheels are held in place by hubs which are also steel.
- Diagonal steel bracing and energy dissipaters are present in the main upper body of the floats.

Prior to the field study, the possibility that the current floats included steel interventions had been suggested, but the extent of the steel's incorporation had not been verified.

The initial hypothesis was that the steel had been included in order to meet safety requirements, and that this might represent an externally imposed regulatory constraint on an historic cultural practice. It had also been suggested that this might be analogous to the more general trend in Japanese structural engineering towards prescriptive standards requiring contemporary braced seismic-designed building structures in new construction. This was a particular concern of the Civic Cultural Heritage Network Tottori, who are interested in the preservation and reintroduction of traditionally carpentered unbraced post and beam building techniques.

However, dialogue with the float teams suggested that the principal reason for the inclusion of steel was the great expense of repairing or replacing damaged floats. The inclusion of steel in the chassis, Mikoshi and masts means that, in most cases, only the ram-assembly requires yearly replacement. It was noted that prior to the inclusion of diagonal steel ties and energy dissipaters in the Mikoshi, hemp rigging of the type used to restrain the lantern curtains would have been used in a not dissimilar manner. Due to the level of redundancy in the structural system and the introduction of steel bracing and energy dissipaters, it is difficult to determine the relative contribution of the various traditional and modern systems contributing to the resistance of the dynamic forces imposed by the collision and to the energy dissipated. However, these systems are likely to include:

- The inverted pendulum of the mast,
- The air resistance of the lanterns,
- The flexibility of the primary ram and ram-assembly,
- Dissipation of energy in the hemp binding and contact friction between ram-assembly timbers,
- Dissipation of energy through contact friction in carpentered joints,
- Steel cross-bracing and energy dissipaters in the upper part,
- The active response of the team members riding the float, including at least two drummers and a number of team members in the rigging to relight extinguished lanterns.

Damage to the ram-assembly was sustained by a number of floats, including in one case the complete failure across-the-grain of a transverse ram-assembly beam, resulting in immediate cessation of the duel. Permission was also granted to carry out a supervised visual inspection of the ram-assembly of one of the floats the morning after the duel. Permission was not granted to photograph the damage to the inspected float.

Visible damage was sustained by the ram structure of the floats. In particular, degradation of the end grain of the primary ram due to repeated impact was evident. Although damaged, the end-grain remained confined by the steel hoop at the end of the ram. Indentation of the transverse ram beams was also noted where impact has been sustained where the primary rams had 'missed' and struck the ram-assembly. The chassis, Mikoshi and mast did not appear to have sustained damage, although close inspection of the mast was not possible.

3 METHODS

The geometry of the floats was surveyed using a non-prism type total station. Figure 3 shows all the points for measuring the geometry of one of the floats. The height from the ground to points 6-9 is 4.56m, giving a total height of approximately 5m.

High-resolution digital video of the floats was recorded during the festival using a Nikon D800E camera with a sampling rate of 60 frames per second. This was subsequently increased to 100 frames per second using spline interpolation. The camera resolution was 2592 × 2048, with 8 bit greyscale, extended by processing into about 1/20,000 of the view width (approximately 1 to 2mm on the frame of the float). The measured geometry allowed calibration of the images to physical dimensions, and then digital image correlation to track various points on the structure.

The high-speed camera was placed at ground level, on the lower right hand side of the grandstand. Figure 4 shows the position of the camera and relationship between the coordinate system, the target and camera. Measurements were made for the float shown on the left in Figure 4. The direction of travel of the float is along the X coordinate.

Figure 5 shows the points for digital image correlation on the striped 'Mikoshi' of the float, which sits just above its 'chassis'.

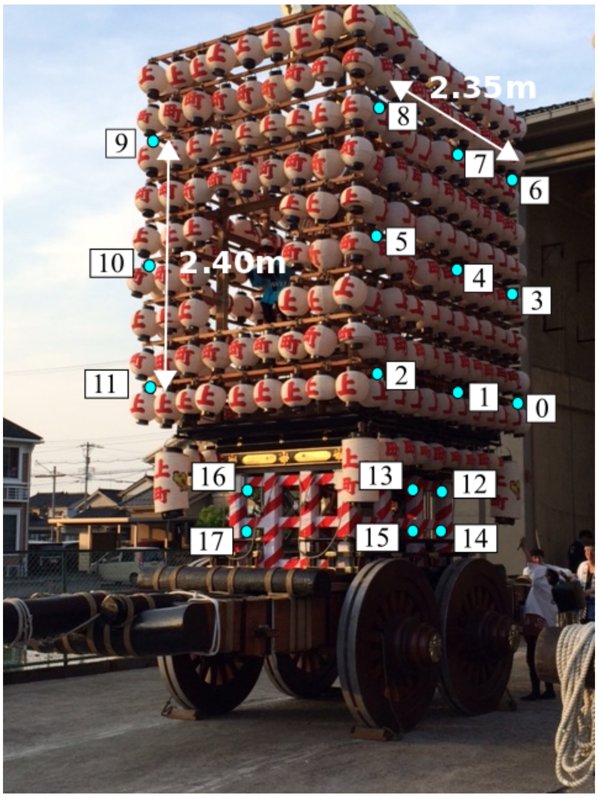

Figure 3: *A float adorned for the duel, with numbers showing the points measured by total station and selected dimensions to indicate scale*

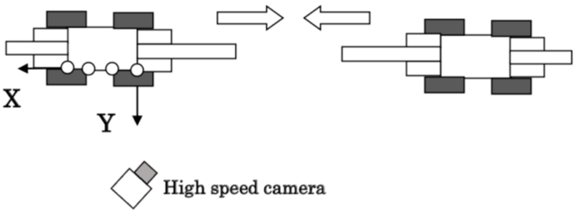

Figure 4: *Camera location in relation to the duelling floats. Z component of displacement out of the page.*

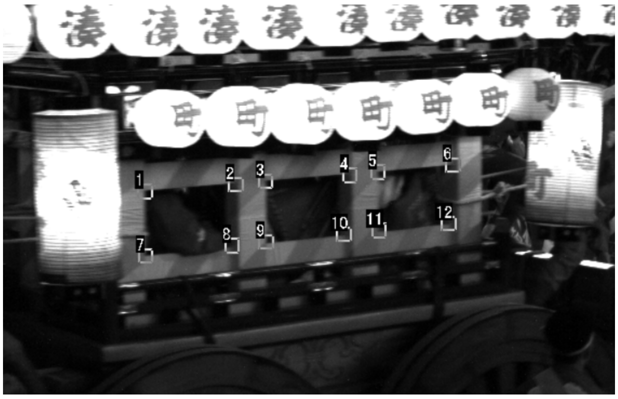

Figure 5: *The full set of measured locations in the Mikoshi of the ram*

These 12 locations were measured for every collision, although in many cases some locations were obscured by lanterns, or could not be followed by image correlation because of substantial changes in lighting due either to the lanterns or camera flashes in the audience. Digital image correlation is most reliable in constant lighting conditions, so a target covered in lanterns, imaged after dark with occasional camera flashes is by no means an ideal specimen! Nonetheless, sufficient points were visible and reliably tracked for all eleven collisions to measure the speed of the float as it approached the collision. In several cases, the striped Mikoshi was visible before and after impact, and in one case the ram was also visible before and after impact.

The camera parameters were determined using the coordinates of the points on the float measured in advance using the total station. Points 3, 4, 9 and 10, used in digital image correlation and shown in Figure 5, correspond to points 12-15, measured by the total station and shown in Figure 3. The measured dimensions of this Mikoshi could therefore be used to calibrate the displacements measured by digital image correlation of the video recordings, allowing for the fact that the points on the target were at various distances from the camera, and also for the distortion due to the camera lens. This allowed measurement of the absolute movement and relative deformations of the float during impact.

A single camera was used to record the video, and therefore only a two-dimensional projection of the movement of the floats. The known geometry of this set of points, however, allowed a pseudo three-dimensional analysis to be carried out, since the location of this grid of points in the image could be mapped onto its true geometry, and the same mapping could be used to map the movement of the points onto their absolute displacements. Evaluation of these recordings is useful in understanding the magnitude of the decelerations of the floats on impact, and their dynamic and dissipative behaviour.

The shooting of the high-speed camera started from the time when the people pushing the float started running. The float was pushed, gathering speed, for approximately 3 to 5 seconds before entering the frame of the video.

4 OBSERVATIONS

The floats are said to weigh between 8 and 10 tonnes, with the lightest float being the only one that retains a timber central mast; the other masts having been replaced with steel circular hollow sections.

Many of the connections between timber members are made by lashing with hemp rope and carpentry connections. Steel, clearly not an original feature, is present too, with very large steel plates and brackets used to connect the ram substructure to the leading lower transverse beam of the chassis, and steel cables bracing the upper parts of the structure.

The duels involve successive one-on-one confrontations between pairs of floats. The floats start out approximately 20m apart and are accelerated by their respective teams of eight people, pulling on hemp ropes and leaping aside at the last moment as the rams collide.

The sudden deceleration on impact causes the back end of the float to lift up dramatically, throwing the team drummers, who ride above and immediately behind the ram, against the unnervingly loose ropes that tie them to the float. The scene is reminiscent of two runaway carriages, ablaze, and careening into each other at speed. Often, the aim of the teams is imperfect, meaning that the rams do not strike concentrically, either catching a glancing blow on the opposing ram or missing entirely, and passing-by to strike the shoulders of the opposing float instead.

5 RESULTS AND DISCUSSION

Every duel which was captured by camera produced data on the approach velocity of the floats, but the analysis of the impact was only carried out for occasions on which the collision was accurate and the two rams met each other concentrically, resulting in very little sideways movement in the Y direction of Figure 2.

The camera captured a brief time before collision, ranging from 0.4 to 1.0 seconds. During this time, the velocity was very near to constant. The velocity of the floats on the approach to impact were measured on 11 occasions. This gave a mean velocity of 2.9 m/s, with a coefficient of variation of 4%. Thus, although the floats were pushed by people, the velocity they reached before impact was very consistent. This is considered to be a result of the collisions being much-repeated actions for which the people pushing the float had trained.

Digital image correlation was used to track various parts of the float in the few seconds before, during and after the collision. Figure 6 shows the movement of the ram, near where it makes contact with that of the competing float. This analysis gives the total resolved displacement of the X and Z components of displacement, as defined in Figure 4.

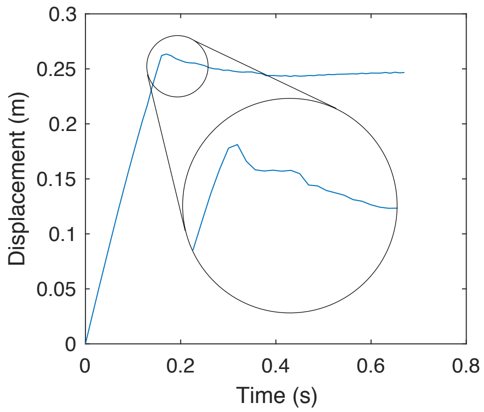

Figure 6: *The displacement of the ram before, during and after a collision, with the collision magnified*

Further analysis considered only the X component, by resolving displacements along the direction of the initial velocity of the float.

The float has been gradually brought up to a steady initial speed of approximately 2.8m/s, shown by the constant change in displacement with time at the start of the measurement, and is brought to a halt by the collision.

Figure 7 shows a comparison of the time-history of movement of two different parts of the float, shown in terms of displacement, velocity and acceleration. The solid line shows the movement of the ram, approximately 1m from the end which makes contact with the ram of the opposing float; the dashed line shows the movement of a point on the Mikoshi, which sits on top of the chassis, shown as point 12 in Figure 3 and point 4 in Figure 5. The Mikoshi was observed to move approximately as a rigid body, and so the displacement, velocity and acceleration for the other points on the Mikoshi are very similar, although the small relative displacements between them could be used to assess their contribution to the structural resistance and energy dissipation in the float, given more information on the structural form of the float.

It can be seen that the reversal of displacement of the ram in Figure 6 is not present in Figure 7, which considers only movement in the X direction. The reversal was due to the vertical movement of the ram as the float rocked at impact. This highlights the importance of considering the component of displacement in the direction of the impact force.

The acceleration of the point was measured by numerically differentiating the displacement time-history. The challenge of designing these 8 to 10 tonne structures to resist the inertial forces due to this acceleration is not trivial, as can be demonstrated by comparison with seismic design of a timber building. A small (45m^2) and light (250kg/m^2 [5]) house would weigh approximately 11 tonnes, of the same order of magnitude as the weight of these floats. The magnitude of the acceleration of the floats is far higher than would be expected in an earthquake, although the shaking in an earthquake continues for many cycles. The highest measured horizontal ground accelerations in the 2010 Maule Earthquake (Magnitude 8.8) in Chile were approximately 10m/s^2 [6].

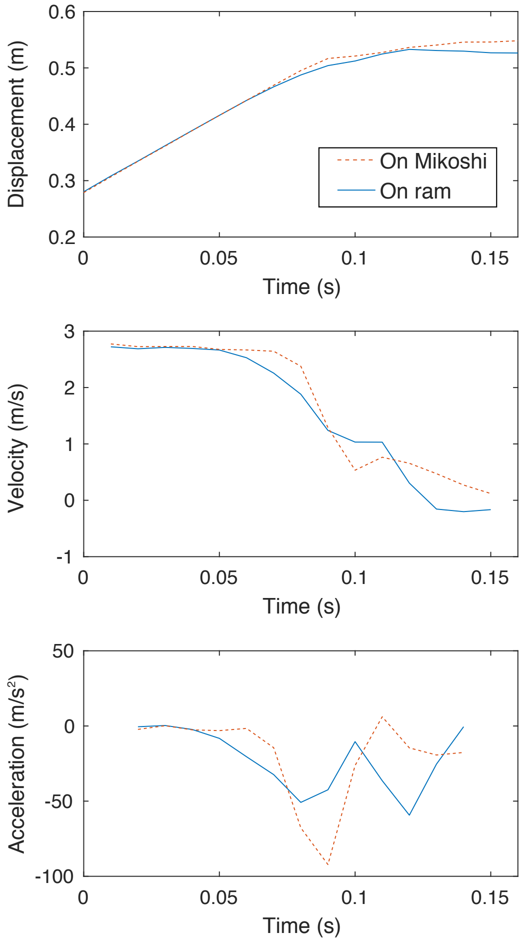

Figure 7: *The movement of the ram compared with that of the Mikoshi (point 4), in terms of displacement, velocity and acceleration*

The 95m/s^2 peak acceleration shown in Figure 7 may be exaggerated because of the relatively low frame rate of the image capture, but there are three points measured with over 50m/s^2 acceleration, so it appears that accelerations of this level did occur. The accelerations experienced by these floats under impact are therefore extreme even in comparison with an earthquake.

Figure 7 shows that the highest acceleration actually occurs in the Mikoshi, rather than at the ram, as it decelerates from the approach speed of 2.8m/s^2 to zero. This may be due to the much lighter part of the float restrained by the Mikoshi. The ram is contiguous with parts of the float with high mass, which require a high force to produce a deceleration. The Mikoshi, in contrast, restrains the much less massive mast and rigging, which could be decelerate much more rapidly for a given force.

The graphs in Figure 7 show the lag between the initial deceleration of the ram and that of the Mikoshi. This is reasonable, since the ram makes direct contact with the opposing float, and the force of that impact must be transferred through the structure to the Mikoshi.

The deceleration at the ram builds up gradually. This depends in part on the stiffness of the other float. If the two floats were identical, then we would expect the contact point between them to stop instantaneously, with a very high acceleration. The different and non-linear behaviour of the two floats leads to a more complex interaction, however.

The ram initially decelerates, until the deceleration of the Mikoshi is initiated, perhaps by the impact of the ram assembly onto the rest of the chassis. This impact then arrests the deceleration of the ram assembly, and it moves forward at constant velocity again at around 0.1 seconds in Figure 7. There then appears to be a secondary impact of the ram onto the other float, giving another deceleration of the ram, and gradually the Mikoshi, down to zero velocity.

There is a residual displacement of approximately 20mm at 0.15 seconds, where the velocity of each element is near zero. This suggests that there are some small gaps and slack elements in the system, which are closed up during the impact. The high acceleration of the Mikoshi is therefore presumed to occur at the time that this slack is taken up.

There is very little evidence of oscillatory behaviour, suggesting a highly damped structure.

6 CONCLUSIONS

The initial field study suggests that the behaviour of the Fushiki Hikiyama floats is of engineering interest with respect to the behaviour of wooden structures subject to dynamic and particularly impact loading. Although the steel is a relatively modern intervention, the diagonal bracing is thought to be a fairly direct replacement for hemp rigging. This suggests that the structural principles may be relatively unchanged, although the relative stiffness of the components may be very different from the original. The authors are exploring further opportunities to monitor the floats in-situ and this, along with a detailed structural survey of the floats, would create a more complete picture of the dynamic behaviour of the floats during the duel.

A quantitative analysis has been made of the collisions between festival floats in the Fusiki Hikyama. The floats are predominantly constructed from wood, with the modern addition of steel reinforcement at highly loaded points. They sustain, for a short duration, accelerations far exceeding those of an earthquake.

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