AN ANALYSIS OF DIFFERENT POLE VAULTING POLE LOAD-DEFORMATION TESTING REGIMES

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This study aimed to determine whether differences in the pole elastic energy characterisation were evident between quasi-static and dynamic load-deformation testing on pole vault poles. A total of 12 pole vault poles were tested from three different manufacturers, who each utilise different materials within their pole construction processes. A quasi-static and a dynamic pole bending test was performed on each pole utilising a custom built rig. A 3D load cell was positioned in series with the rig to obtain the forces required to develop a load-deformation curve for each trial. The results of the bending trials demonstrate a noticeable difference in the load-deformation curves obtained via the two methods, most notably regarding the degree of hysteresis between the loading and unloading phases and the resultant elastic potential energy calculations.

KEY WORDS: quasi-static, dynamic, elastic potential energy.

INTRODUCTION: Effective performance in the pole vault event is heavily reliant on the efficient transfer of energy throughout the vaulting phase. Key to this energy transfer is the storage and recovery of the elastic potential energy (EPE) of the poles used in the pole vault to transfer the initial kinetic energy of the vaulter to gravitational potential energy.
Pole vault poles are typically characterised by the manufacturers using simple summary variables related to the how stiff the pole is (flex rating), the length and diameter of the pole and a safety load rating. The flex ratings are derived in various ways by each manufacturer, but are traditionally represented by the results of a simple static load test. These methods are not representative of the poles behaviour during a dynamic vault and do not provide the level of information required to quantify the elastic energy absorption and conversion potential and load deformation properties of the poles.
Research into the pole vaulting technique has traditionally separated the pole and the vaulter from an analysis viewpoint, rather than consider an integrated approach. Previous pole investigations have concentrated on modelling the pole structure and bend without determining its integration with the vaulter (Fukushima et al., 2013; Morlier et al., 2008). Similarly, previous investigations focussing on the pole vaulter have made many assumptions about the pole’s properties, thereby limiting how the poles perform during the elastic storage and recovery phases of the vault. The energy stored in the pole during a vault is a more recent aspect of the vault to be analysed, although there are many improvements that can incorporate specific pole characteristics into overall energy within a vault.
This study sought to determine whether different experimental protocols for characterising a poles load-deformation curves and calculated EPE result in varying results. Specifically, a quasi-static versus dynamic loading of the poles were to be investigated. The end result was to develop a more specific pole energy calculation that best represented the individual poles EPE that could then be incorporated into energy calculation for a complete vault.

METHODS: A total of 12 poles were used to conduct the load-deformation testing from three different manufacturers. Full details of the poles are listed in Table 1.

Table 1. Summary of pole manufacturer information for the tested poles

Pole Number	Manufacturer	Flex Rating (cm)	Weight Rating (lb/kg)	Length (m)	Construction Material
1	A	21.5	145/66	4.30	Fibreglass
2	A	20.9	150/68	4.30	Fibreglass
3	A	17.0	175/79	4.60	Fibreglass
4	A	17.5	170/77	4.60	Fibreglass
5	A	22.1	160/73	4.45	Fibreglass
6	A	21.8	160/73	4.45	Fibreglass
7	B	19.7	155/70	4.30	Fibreglass/Carbon
8	C	21.0	150/68	4.30	Carbon
9	C	21.5	150/68	4.30	Carbon
10	C	22.0	145/66	4.30	Carbon
11	A	16.0	190/86	5.00	Fibreglass
12	A	15.4	200/91	4.90	Fibreglass

A custom designed pole bending system that could control the pole bending while recording the transmitted load and the resultant amount of bend produced in the pole, was used for the data collection (see Figure 1). This consisted of a mechanical winch system attached to a 3D load cell. A steel tape measure was then attached to the end of the pool and videoed to provide details of the magnitude of the pole bend at each time epoch. An LED was situated within the field of view to synchronise the load cell recordings with the video.

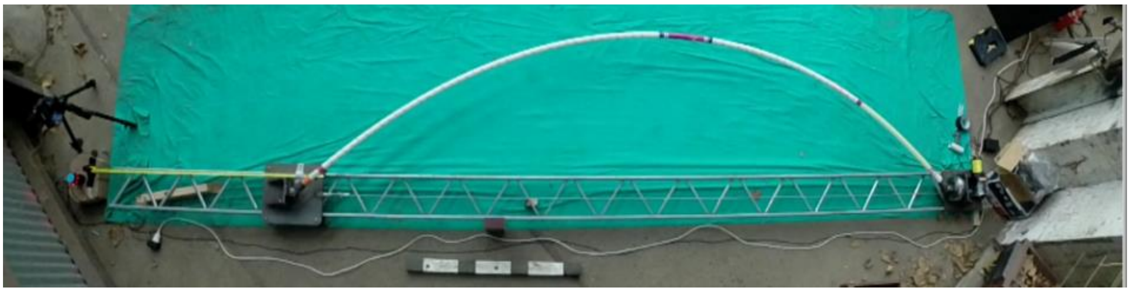

Figure 1. Above view of the pole bending system during load-deformation testing.

The quasi-static protocol involved the poles being compressed in small increments, with the transmitted forced measured statically at each point with the load cell. The final degree of compression was set to replicate the degree of deformation quantified within a pole vault trial. This same process was used in reverse when releasing the compression until the pole was back to its extended position. Across the compression and release approximately 50 points were recorded. The dynamic protocol followed a similar procedure to the quasi-static, however the compression and release occurred continuously. The pole was compressed up to the same displacement point, followed immediately by a controlled continuous release. This created a full compression and release trial lasting between 40 and 60 seconds where the force was recorded and matched again to the displacement from the video.

The force and displacement data were then inputted into a custom designed analysis program written in IGOR Pro (WaveMetrics IGOR Pro 6) software for further analysis.

Equation 1 below is the custom fitting function created in the program to calculate the force at x displacement:

$$Force(x) = a + b(x - x_0) - \frac{c}{(x - x_0 + d)} + h\left(\frac{x - x_0}{f}\right)^g \quad (1)$$

Through manipulation of the coefficient values, the same function is used for both the loading and unloading and the fit error calculated within the analysis program. This added together the difference between the actual data and the fit function at all points along the curve. As the coefficient values were manipulated, this error updated so that it could be minimised to find the best fit to the data.
The energy in the pole is then calculated by finding the area underneath the curve or the integration of Equation 1. For calculation of the energy stored in the pole as a function of displacement (x) the above function is integrated to become Equation 2 below:

$$Elastic\ Potential\ Energy(x_s,x_f) = a(x_f - x_s) + \frac{b}{2}(x_f{}^2 - x_s{}^2) + bx_0(x_f - x_s) - c\ln\left\{\frac{d+x_f-x_0}{d+x_s-x_0}\right\} + \frac{fh}{(1+g)f^{(1+g)}}\left\{(x_f - x_0)^{1+g} - (x_s - x_0)^{1+g}\right\} \quad (2)$$

This allows the energy stored in the pole to be calculated at any amount of bend and therefore the difference in the energy stored in the pole and then recovered during the unloading. The energy lost can be calculated by taking the total energy for the loading curve and subtracting the energy of the unloading curve.

RESULTS: Figure 2 highlights an example load deformation curve for one pole, in both the quasi-static and dynamics loading trials.

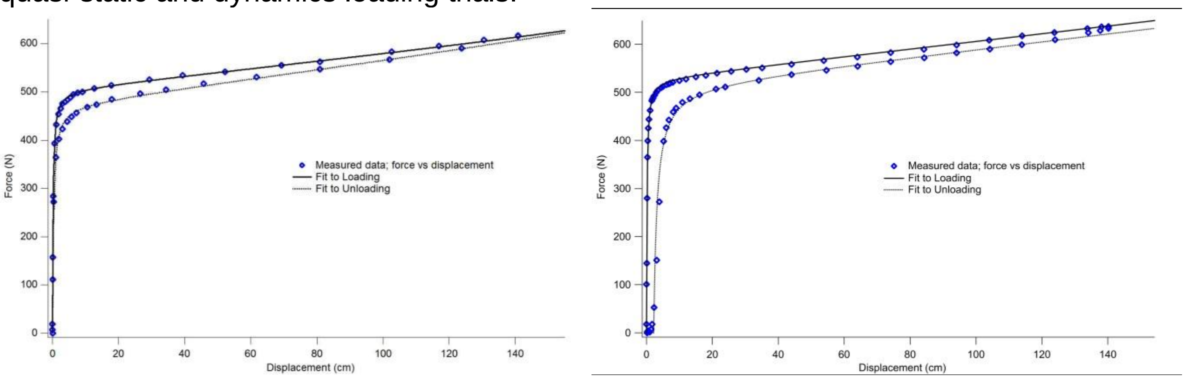

Figure 2. Example load-deformation for the quasi-static and dynamic trial for the same pole

The energy equation (Equation 2) enables the calculation of the energy stored and recovered from a bending trial for each pole. The energy lost through the bend are also quantified and, displayed in table 2 along with the percentage of energy lost.

DISCUSSION: The bending characteristics for the same pole under the two methods of bending appear to show some differences in the fitted curves. When subjected to dynamic bending, greater force is required to bend the pole to match the displacement in the quasi-static. This change between the two methods can be explained by a settling of the recorded force output from the pole over time, as observed during the quasi-static testing. During a quasi-static trial the pole is compressed and then stays static in this position while the force measure is recorded. This time period allows the force to settle at a decreased load value while still holding the same amount of bend in the pole. When a pole is bent dynamically, this epoch is reduced and therefore the force measure is greater across the trial. This reinforces that any pole characterisation should be conducted in conditions that best represent an actual vault. During a vault, the pole vaulter loads and unloads the pole in a very short period of time (<2s) and therefore, while not exactly replicating the deformation rate, the slow dynamic method used in this study is a closer representation of the mechanics occurring during a vault.

Table 2. Force and energy values from quasi-static (Quasi) and dynamic (Dyn) trials.

Pole #	Max Force (N)		Max Energy (J)		Energy Return (J)		Energy Loss (J)		% Loss	
	Quasi	Dyn	Quasi	Dyn	Quasi	Dyn	Quasi	Dyn	Quasi	Dyn
1	615.2	636.1	781.4	795.7	753.6	748.0	27.8	47.7	3.6	6.0
2	643.2	653.1	788.7	800.2	761.5	719.1	27.1	81.2	3.4	10.1
3	872.9	869.0	1211.1	1188.6	1165.4	1127.7	45.8	61.0	3.8	5.1
4	846.9	846.2	1157.4	1145.6	1114.4	1075.3	43.0	70.4	3.7	6.1
5	744.4	755.4	1025.4	1022.5	990.6	958.9	34.8	63.5	3.4	6.2
6	753.0	761.3	1019.2	1045.8	986.6	986.5	32.6	59.3	3.2	5.6
7	676.8	675.2	675.5	660.1	645.9	612.5	29.6	47.7	4.4	7.2
8	662.4	641.7	822.5	774.9	795.0	740.8	27.5	34.1	3.3	4.4
9	643.8	642.0	790.7	745.7	763.8	653.5	26.9	92.2	3.4	12.4
10	611.5	632.7	747.3	761.9	720.4	678.7	26.8	83.1	3.6	10.9
11	945.1	948.9	1329.4	1310.3	1278.9	1196.5	50.5	113.8	3.8	8.7
12	1030.1	1042.7	1423.8	1431.2	1381.4	1309.6	42.4	121.5	3.0	8.5

The second observable difference between the methods is during the unloading curve at small displacements. During the quasi-static trial, as the pole straightens, the force displacement curve begins to closer match the loading curve. This is not the same for the dynamic trial as the unloading curve exhibit marked hysteresis. This difference between the two methods of bending has significance to the vaulting action as it can be shown to explain a portion of energy lost when vaulting. The previously mentioned rest time in the quasi-static method helps to explain this discrepancy. As the pole is unloaded dynamically, force decreases quicker. However, if quasi-statically unloaded, the force increases back up to hold the pole at that displacement level.

The graphs in figure 2 show an observable difference between the loading and unloading phases of the bending. A component of the energy lost during a vault has been proposed in previous research to be due to properties of the pole and its ability to store energy (Arampatzis et al., 2004). The degree of hysteresis in the pole shown in the graphs is a form of energy loss that has not previously been explained in pole vault analysis. By quantifying the energy lost between the loading and unloading pole bending trials, this energy loss can be integrated within a full pole vault analysis, incorporating pole-specific energy information.

CONCLUSION: The quasi-static method for pole bending is more simplistic for data collection and analysis. However, to increase the validity to reproduce the characteristics of how individual poles behaves during actual vaulting, dynamic pole bending testing is crucial.

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