Predictive Damage Assessment of Infrastructure using Machine Learning on Full-Scale Aluminum Pedestrian Bridges

Sagnik PAUL[a] and Ann C. SYCHTERZ*

*Assistant Professor, Civil and Environmental Engineering, University of Illinois Urbana-Champaign
205 N Mathews Ave, Urbana, Il, 61801
asychter@illinois.edu

[a] Research Assistant, Civil and Environmental Engineering, University of Illinois Urbana-Champaign

Abstract

US highways are rated a "D" grade due to degrading road conditions that cost motorists an additional $130 billion per year on road induced vehicle repairs. Overcoming this challenge requires a new approach to researching the in-situ condition of pedestrian bridges to reduce risk to human life, cost of insurance claims, and cost of repair. Uncertainty statistical parameters will generate scenarios for are domain-specific and new parameters would focus on the economic impact and the insurance assessment of the structure. Training data for the hybrid machine-learning algorithm will utilize datasets of a full-scale aluminum pedestrian bridge. Pedestrian bridges are of extreme importance in the society for easier movement of people as well as to reduce the chances of accident. Researchers are constantly trying to pave ways to increase the use of pedestrian bridges all over the world. With new technologies in construction, the study of dynamic properties of pedestrian bridges is currently in high-demand due to the age of infrastructure and the importance of infrastructure to the United States government initiatives. Engineers must design bridges to be resilient against natural hazards as well as to be resilient against human excitation, causing sway of the bridge. This paper presents the relation between vibration, the first natural frequency, and damping coefficient with the walking speed and age for a 40-ft and 70-ft aluminum pedestrian bridge. Machine Learning algorithms are applied on the dataset to establish models ideal for classifying the walking speed and age of the bridge.

Keywords: Pedestrian Bridge; First Natural Frequency; Damping Coefficient; Clustering; Nearest neighbor;

1. Introduction

Structural health monitoring and damage detection has not yet been extensively studied for pedestrian bridges compared with highway bridges. Only recently have design codes such as the American Association of State Highway and Transportation Officials (AASHTO) and the Canadian Standards Association (CSA) developed chapters for unique challenges of pedestrian bridge design. For pedestrian bridges, there lacks a body of knowledge from decades of bridges surveys and a domain intuition that exists for highway bridges. Structural Health Monitoring (SHM), is commonly implemented on large highway bridge whereby sensors are install on or around the structure to continuously collect data to assess the state of the bridge. This is particularly useful to determine progressive failure, changes in how load is distributed through the structure due to corrosion, cracking, and settlement of soil throughout the years. Pedestrian

bridges are one of the safest ways for people to navigate avoiding traffic [1]. These bridges help in crossing of railway tracks and roads, which allows free movement of vehicles and reduces the risk of accidents. Such bridges are also common in hiking trails and other tourist sights allowing easier access to several spots in various areas. Thus, health monitoring of such bridges is of prime importance for the safety of the people.

Although use of pedestrian bridges increases the time of travel for pedestrians, it reduces the rate of causality [2], [3]. The use of pedestrian bridges can be promoted by carefully designing them such that it falls on the normal way of the traveler [4]. Moreover, the aesthetical environment associated with a pedestrian bridge also reflects the choice for it to be used[5]. Research is being carried out across the world to understand the perception of the pedestrians and figuring ways to improve the usage of pedestrian bridges [6], [7].

Human induced load and the way of interaction of human with the structure is of extreme importance for pedestrian bridges [8]–[10]. The motion of the bridge may be affected depending on the amplitude of vibration which can cause change in the human interaction with the bridge [11]. Various dynamic models have been proposed for analyzing pedestrian bridges that take human interaction into consideration [12]–[16]. Pedestrian bridges have become more susceptible to vibrations with many new construction trends [17]–[20]. There have been several reports of lively pedestrian bridges and the infamous swaying of the London Millennium bridge caught the attention for its design [21]–[24].This phenomenon occurs when the natural frequency of the bridge matches the human induced frequency [25]. Engineers should be more careful with the design if the natural frequency lies in the range of 0.9 Hz to 2.5 Hz [26]. This paper studies the how the natural frequency and damping changes with walking speed and time in two pedestrian bridges of different lengths.

Cost assessment of Structural Health Monitoring has been studied in other fields such as offshore wind turbine [27] and aviation [28]. These industries have high-risk environments in addition to several large companies with extensive research and development teams. With the infrastructure bill having been passed in the United States to support repair of American roads, buildings, and bridges, these examples will form the precedent of how life cycle assessment, risk-assessment, insurance values, and sustainability will move forward for pedestrian bridges.

2. Methodology

2.1. Experimental Procedure

Two aluminum pedestrian bridges of lengths 40-ft with eight bays and 70-ft with fourteen bays are constructed in the laboratory. Individual persons of varying weights are made to walk (or run) on the bridges at various speeds. The experiments were conducted at a rigorous pace over several months to study dynamic properties of the bridge. The speed of walking varied from 100 beats per minute (BPM) to 180 BPM. The speeds of less than 150 BPM are classified as ‘walking’ while the speeds greater than 150 BPM is classified as ‘running’. A more details of the speed of movement of an individual on the bridge is shown in Table 1. Table 1 also mentions the weights of the persons that walked on the field. The experiment is conducted over 16 days for the 40-ft bridge while it lasted for 10 days for the 70-ft bridge. The temporal stage is divided into stages of ‘initial’ and ‘later’. Table 1 shows the details of the ‘initial’ and ‘later’ classifications.

Table 1: Parameter details of walking speed, temporal stage, and weights of individuals.

Walking Speed (BPM) (for 40 ft and 70ft bridge)	**Walking**					**Running**		
	100	110	120	130	140	160	170	180
Temporal stage (days) (for 40 ft bridge)	**Initial**				**Later**			
	1	8	9	10	13	14	15	16
Temporal stage (days) (for 70 ft bridge)	1		2		9		10	
Weights of individuals (lbs)	125	135	120	172	142	128	150	148

The accelerometer readings are obtained which are attached to the bridge. The first lateral and vertical natural frequencies are obtained from the Fast Fourier transformed accelerometer data. The damping coefficient at the first natural frequencies are computed by the half power bandwidth method [29]. Figure 1 shows the detailed process of obtaining the first natural frequency for one of the sample data. A total of 1661 experiments are conducted on the 40-ft bridge and 692 experiments conducted on the 70-ft bridge. Only the first natural frequency is examined since it is closer to the pedestrian exciting frequencies which can cause swaying the bridge.

2.2. Results and Observations

Figure 2-5 shows the plot of the mean and standard deviation of the first natural frequency and its corresponding damping coefficient for lateral and vertical modes with respect to walking speed and temporal stage. Based on these data it is observed that the first lateral natural frequencies are lower than the first vertical natural frequencies. The first lateral natural frequencies also lie within the critical range of 0.9 Hz to 2.5 Hz and are more important for the design of a pedestrian bridge.

The mean value of the first lateral natural frequency increases with increase in walking speed for both the 40-ft and 70-ft pedestrian bridge. However, there is no prominent relation present between the first vertical natural frequencies of both bridges. The mean damping coefficient at the first natural frequencies of lateral and vertical modes also show an increasing trend with increasing walking speed for both the bridges.

However, there is no specific relation between the first natural frequency and the temporal stage can be established. With respect to damping coefficient, for 70 feet bridge, the mean damping coefficient is slightly higher for the 'later' stage for lateral and vertical modes. However, there is no prominent relation established for the 40-ft bridge in either case.

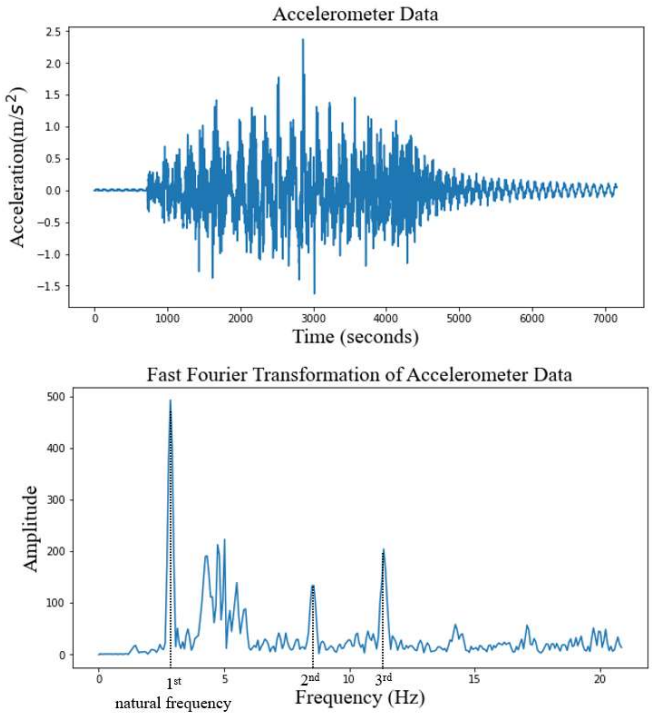

Figure 1: Depiction of obtaining first natural frequency from accelerometer readings by Fast Fourier Transformation.

2.3. Clustering

The experimental data will be useful to establish a relation between the first natural frequency and damping coefficient with walking speed and temporal stage. The data is divided into two classes for walking speed and temporal stage as mentioned in Table 1. Unsupervised algorithm of K-means clustering is used to identify two clusters of the data with first natural frequency and damping coefficient as its parameters. The two clustered data are now compared with the actual classifications of walking speed and temporal stage. This will produce a measure how successful is the clustering algorithm to identify the respective classes based on the dynamic properties of the bridge. Figure 6 shows the clustering classification results for the 40-ft bridge with respect to walking speed. The 'walking' and 'running' are two clusters formed by clustering. The 'true walking' refers to those data points which are correctly clustered with 'walking' and belongs to 'walking', while 'false walking' refers to those data points which are clustered with walking but belongs to 'running'. The 'true running' and 'false running' means the opposite here. The exact percentage of successful classifications are represented through a confusion matrix in Table 2. Table 2 also shows the confusion matrix for all the cases for different types of bridges and for lateral and vertical modes.

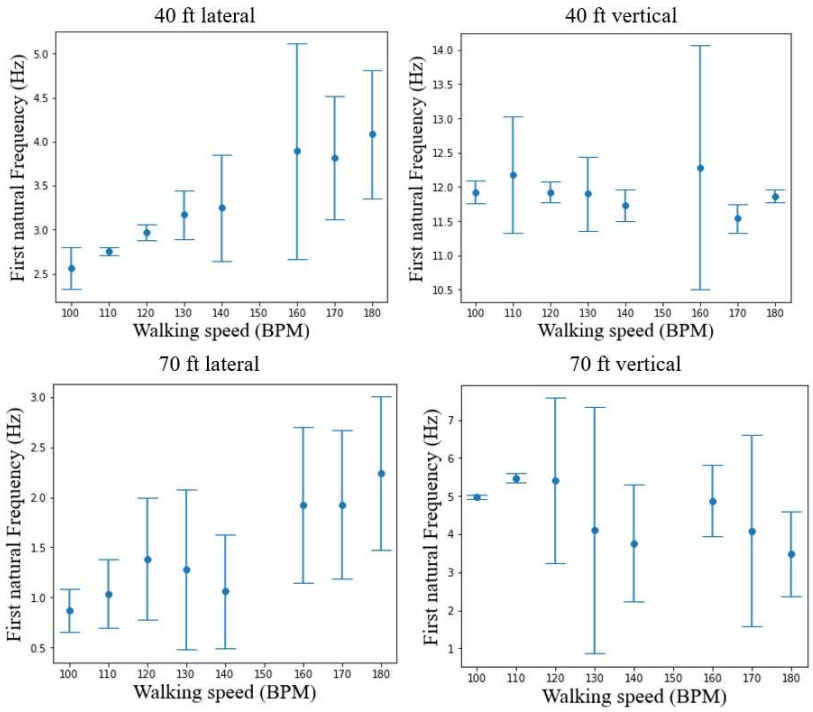

Figure 2: Mean and standard deviation of first natural frequency with respect to walking speed.

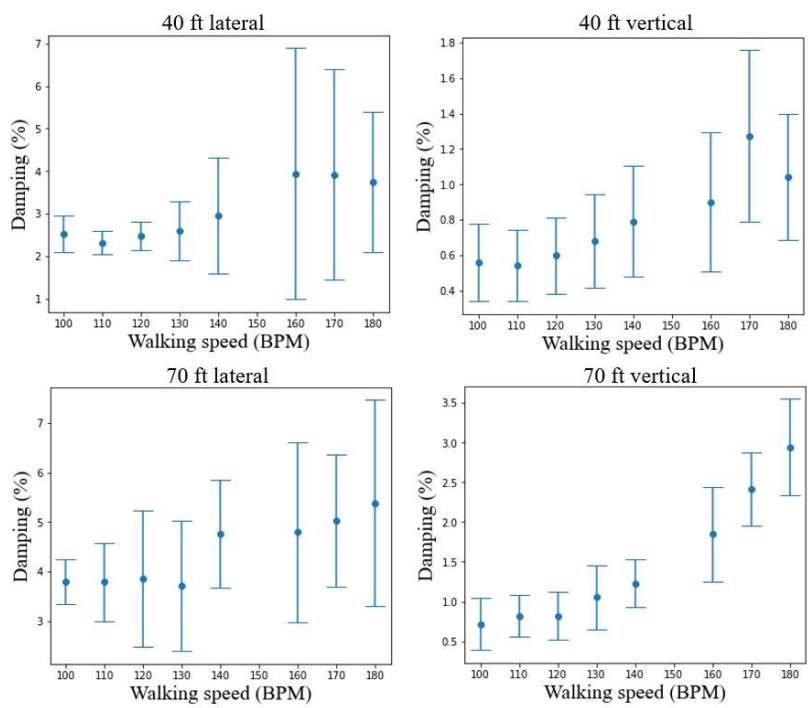

Figure 3: Mean and standard deviation of damping coefficient with respect to walking speed.

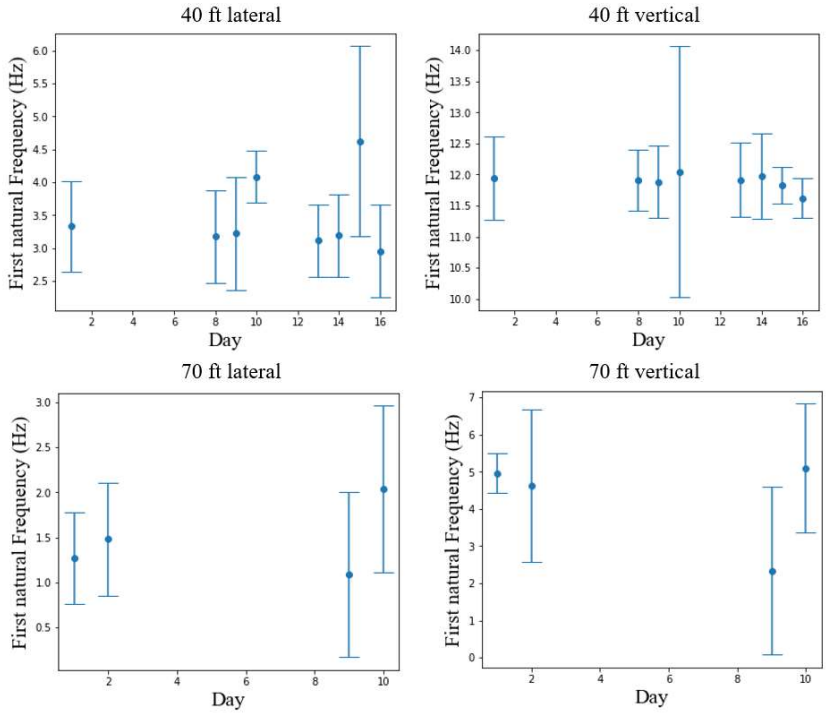

Figure 4: Mean and standard deviation of first natural frequency with respect to temporal stage.

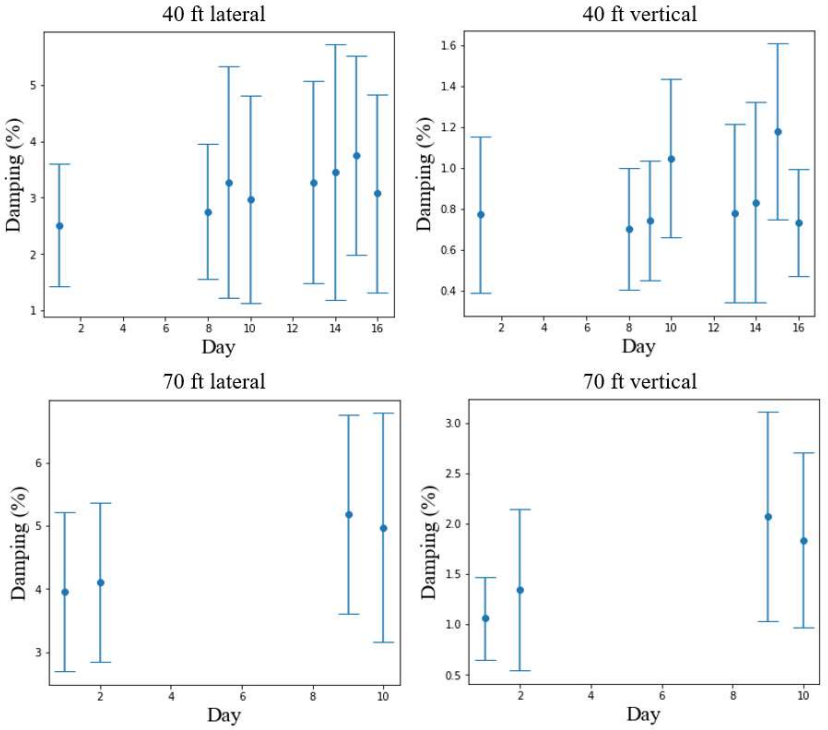

Figure 5: Mean and standard deviation of damping coefficient with respect to temporal stage.

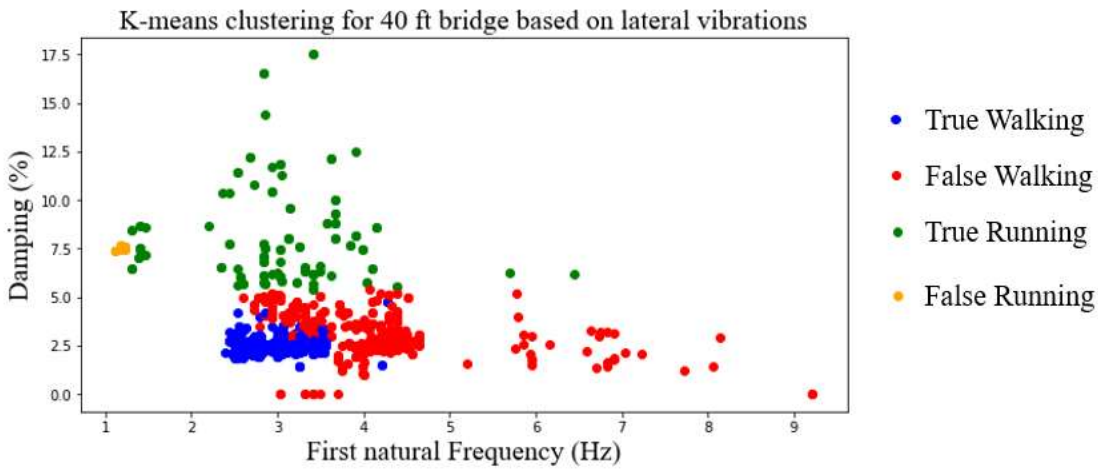

Figure 6: Classification results based on K-means clustering for 40-ft bridge in lateral vibrations with respect to walking speed.

Table 2: Confusion matrix for the classification results for all the cases by K-means clustering.

40ft lateral	Actual	Predicated		Actual	Predicated	
		Walk	**Run**		**Initial**	**Later**
	Walk	98.21%	1.79%	**Initial**	93.76%	6.24%
	Run	81.76%	18.24%	**Later**	89.25%	10.75%
	Overall	**66.53%**		Overall	**55.63%**	
70ft lateral	Actual	Predicated		Actual	Predicated	
		Walk	Run		**Initial**	**Later**
	Walk	79.20%	20.80%	**Initial**	76.43%	23.57%
	Run	65.80%	34.20%	**Later**	70.22%	29.78%
	Overall	**61.71%**		Overall	**58.09%**	
40ft vertical	Actual	Predicated		Actual	Predicated	
		Walk	**Run**		**Initial**	**Later**
	Walk	99.30%	0.70%	**Initial**	98.67%	1.33%
	Run	97.73%	2.27%	**Later**	98.69%	1.31%
	Overall	**60.77%**		Overall	**54.03%**	
70ft vertical	Actual	Predicated		Actual	Predicated	
		Walk	**Run**		**Initial**	**Later**
	Walk	99.30%	0.70%	**Initial**	99.51%	0.49%
	Run	99.61%	0.39%	**Later**	99.28%	0.72%
	Overall	**62.10%**		Overall	**59.62%**	

The overall performance is best for lateral vibration in the 40-ft bridge for classification of walking speed. There exists a consistent relation between walking speed with first natural frequency and damping coefficient compared to the others. Moreover, the classification is better for 'walking' than 'running' because the variation of the data points for 'running' is much larger compared to that of 'walking' in general for all cases. The classification with respect to temporal stage is slightly poorer compared to that with walking speed. The variation of the data as well as lack of prominent trend in relation is the reason for such behavior.

2.3. K-nearest neighbor

K-nearest neighbor is another classification model that is applied on the dataset which portrayed improvement. The total dataset is split into a training set and a testing set. Approximately a little over 20 percent of the total number of samples is randomly chosen as the test set while the rest is used for training the model for all the four cases. The results are shown in Table 3 in the form of confusion matrix. The reason K-nearest neighbor produces better results compared to clustering since there are several clusters of similar data instead of one single cluster as shown in Figure 7. The number of nearest neighbors in each category is chosen by minimizing the test data efficiency.

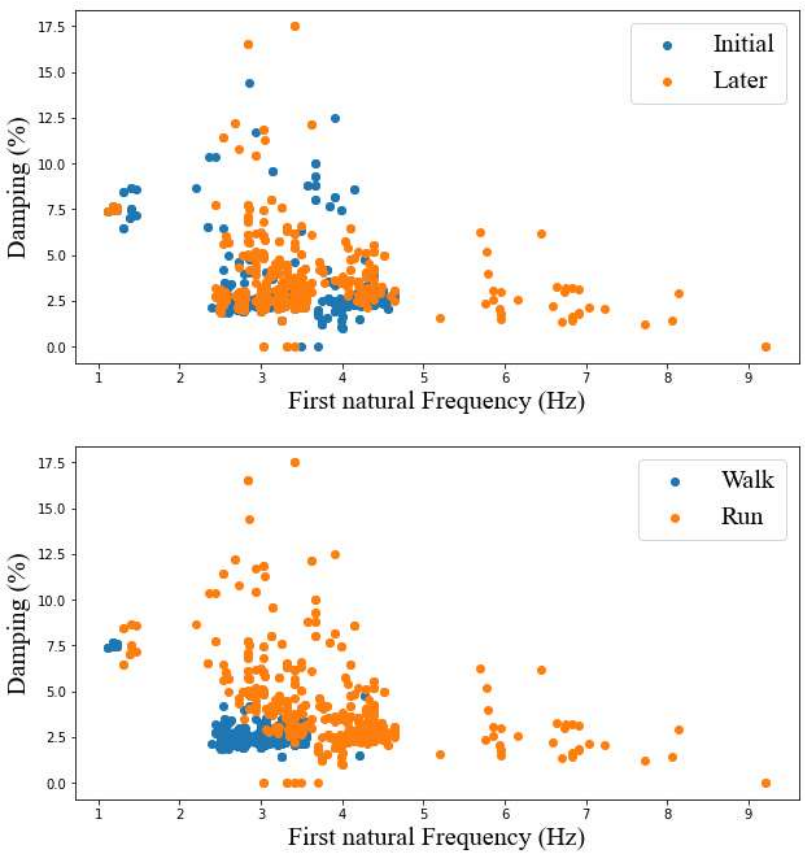

Figure 7: Data for 40-ft bridge with lateral vibrations.

Table 3: Confusion matrix for the classification results for all the cases by K-nearest neighbor.

40ft lateral		Actual	Predicated			Actual	Predicated
			Walk	**Run**			**Initial** **Later**
		Walk	97.22%	2.78%		**Initial**	79.23% 20.77%
		Run	2.24%	97.76%		**Later**	19.76% 80.24%
		Overall	**97.43%**			Overall	**79.71%**
70ft lateral		Actual	Predicated			Actual	Predicated
			Walk	Run			**Initial** **Later**
		Walk	98.92%	1.08%		**Initial**	91.01% 8.99%
		Run	0.00%	100.00%		**Later**	16.39% 83.61%
		Overall	**99.33%**			Overall	**88.00%**
40ft vertical		Actual	Predicated			Actual	Predicated
			Walk	**Run**			**Initial** **Later**
		Walk	93.95%	6.05%		**Initial**	85.71% 14.29%
		Run	5.93%	94.07%		**Later**	21.43% 78.57%
		Overall	**94.00%**			Overall	**82.29%**
70ft vertical		Actual	Predicated			Actual	Predicated
			Walk	**Run**			**Initial** **Later**
		Walk	100.00%	0.00%		**Initial**	93.26% 6.74%
		Run	3.51%	96.49%		**Later**	21.31% 78.69%
		Overall	**98.67%**			Overall	**87.33%**

3. Conclusions

This study shows a successful characterization of the aluminum pedestrian bridge behavior using K-nearest neighbor as the bridge deteriorated and changed properties over the intensive testing cycle. The natural frequency and damping coefficient changes in a pedestrian bridge with several parameters, including age of the structure. First, the first natural frequencies are of prime importance since it ranges in the critical low frequency that matches with the excitement frequency due to human interaction and should be particularly taken care of by engineers while designing to avoid large amplitude vibration. While weight of the people on the bridge does not have much influence on the dynamic properties of the pedestrian bridges, walking speed and the age of the bridge affect them. Clustering algorithms are a good way to classify the walking speed and age based on the natural frequencies and damping coefficients. K-nearest neighbor shows a better model for the classification of the data.

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