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Experimental Evaluation of Pedestrian-Induced Multiaxial Gait Loads on Footbridges: Effects of the Structure-to-Human Interaction by Lateral Vibrating Platforms

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Abstract: The introduction of resistant and lightweight materials in the construction industry has led to civil structures being vulnerable to excessive vibrations, particularly in footbridges exposed to human-induced gait loads. This interaction, known as Human–Structure Interaction (HSI), involves a complex interplay between structural vibrations and gait loads. Despite extensive research on HSI, the simultaneous effects of lateral structural vibrations with fundamental frequencies close to human gait frequency (around 1.0 Hz) and wide amplitudes (over 30.0 mm) remain inadequately understood, posing a contemporary structural challenge highlighted by incidents in iconic bridges like the Millennium Bridge in London, Solferino Bridge in Paris, and Premier Bridge in Cali, Colombia. This paper focuses on the experimental exploration of Structure-to-Human Interaction (S2HI) effects using the Human–Structure Interaction Multi-Axial Test Framework (HSI-MTF). The framework enables the simultaneous measurement of vertical and lateral loads induced by human gait on surfaces with diverse frequency ranges and wide-amplitude lateral harmonic motions. The study involved seven test subjects, evaluating gait loads on rigid and harmonic lateral surfaces with displacements ranging from 5.0 to 50.0 mm and frequency content from 0.70 to 1.30 Hz. A low-cost vision-based motion capture system with smartphones analyzed the support (T_{su}) and swing (T_{sw}) periods of human gait. Results indicated substantial differences in T_{su} and T_{sw} on lateral harmonic protocols, reaching up to 96.53% and 58.15%, respectively, compared to rigid surfaces. Normalized lateral loads (L_L) relative to the subject's weight (W_0) exhibited a linear growth proportional to lateral excitation frequency, with increased proportionality constants linked to higher vibration amplitudes. Linear regressions yielded an average R^2 of 0.815. Regarding normalized vertical load (L_V) with respect to W_0, a consistent behavior was observed for amplitudes up to 30.0 mm, beyond which a linear increase, directly proportional to frequency, resulted in a 28.3% increment compared to rigid surfaces. Correlation analyses using Pearson linear coefficients determined relationships between structural surface vibration and pedestrian lateral motion, providing valuable insights into Structure-to-Human Interaction dynamics.

Keywords: human–structure interaction; anthropic loads; human gait; synchronization; structural vibrations

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1. Introduction

The limitations of serviceability due to vibrations in civil structures, reported on various occasions in structural engineering, are often related to the dynamic coupling between anthropic loads and the dynamic response of these structures. The dynamic relationships between pedestrians and structures have been extensively documented in the literature for civil structures, such as stairs [1,2], grandstands [3,4], slabs [5,6], and footbridges [7–16]. Footbridges have become one of the most affected structures in terms of vibration serviceability limit state owing to their natural condition of spanning large distances and the progressive incorporation of lighter and more resistant materials in the construction industry, which generates relatively low masses and damping and increases technical and aesthetic demands [17–19]. Consequently, these conditions generate structures that are increasingly slender and flexible, increasing their dynamic sensitivity to excessive vibrations owing to the action of loads induced by human activity [20,21]. The events that occurred on the Millennium Bridge in London during its inauguration support the previously mentioned idea, as excessive vibrations occurred in this structure due to the lateral synchronization of forces induced by pedestrians crossing the bridge and the dynamic response of the structure in this direction. This coupling resulted in accelerations close to 0.25 g with displacements of up to 7.0 cm [22,23].

Dallard et al. [13] initially described the dynamic effects in the Millennium Bridge, and the review conducted by Zivanovic et al. [17] positioned the effects of dynamic Human–Structure Interaction (HSI) as one of the topics of increasing interest in the scientific community during the last two decades [24–26]. However, this event has not been configured as an isolated case because there are historical records of similar situations [27]. The oldest cases for which there is technical reference were the collapse of the Broughton Bridge in the UK due to the dynamic loads induced by the harmonic march of 60 infantry soldiers crossing the structure [28], the lateral vibration affectations on the Toda-Park Bridge in Japan [10], and the Solferino Bridge in France [29]. Additionally, more recent incidents have been reported in this type of structure caused by anthropic forces induced, such as the cases of The Wuhan Yangtze Bridge, China [30]; Pedro and Inês Bridge, Coimbra-Portugal [14,15]; Long Span Steel Bridge, Changi Airport, Singapore [11,12]; Le Ponte del Mare, Pescara, Italy [31]; Goodwill Bridge, Brisbane, Australia [32]; Eeklo Bridge, Belgium [8,9]; and the Folke Bernadotte Bridge, Sweden [33], among others [34–38].

These footbridges, which have been affected by HSI effects, promote the hypothesis of great urban regeneration on a global level, where isolated segments are interconnected with higher technical, aesthetic, architectural, and engineering requirements [39]. This innovative perspective led to a remarkable revolution in the design, construction, and management of these structures. However, their sensitivity to anthropic forces is noteworthy, considering that the dynamic behavior of footbridges is generally associated with frequencies lower than 10.0 Hz. The vertical and lateral frequency content characteristics of these structures, typically between 1.6 and 2.4 Hz, establish a focus of sensitivity to the coupling between their structural vibrations and the pedestrian gait dynamics, which is classified as the most recurrent source of excitation in the footbridges, with a typical frequency content between 0.8 and 1.2 Hz [40]. This implies a latent risk that footbridges and pedestrian gaits may be affected by a synchronization phenomenon.

The coupling effects of anthropic loads with the vibrations of pedestrian bridges are due to the adaptive [41], random [42,43], and nonstationary conditions of the human gait [17,44]. HSI effects in flexible surfaces are configured as an advanced case of synchronization and are composed of three main important aspects: changes in the dynamic properties of the structure due to pedestrians, Human-to-Structure Interaction (H2SI) [45–47]; interactions between pedestrians in crowds, Human-to-Human Interaction (HHI) [48–50]; and changes in the pedestrian gait due to the structure's vibration, Structure-to-Human Interaction (S2HI) [18,19,43,51,52]. Although many researchers have concluded that studies and interest in these topics have increased considerably in recent decades, aspects related to the behavior of the loads induced by the human gait in response to structural vibrations have not been fully detailed or understood [9,53]; for example, the effects of structural vibrations on pedestrian-induced gait loads in vertical and lateral directions simultaneously.

Human-induced gait loads produce a total ground reaction force in each direction composed of two principal contributions: passive and active components of the HSI effects. The passive component is related to the dynamic human response to the vibration of the footbridge; in contrast, the active component is associated with the active motion of the pedestrian on the structure [42,54–57]. The structural vibrations control the dynamic coupling with human-induced loads in a vertical direction. For lateral vibrations, additional

Table 1. *Cont.*

		Test Subject						
		No. 1	**No. 2**	**No. 3**	**No. 4**	**No. 5**	**No. 6**	**No. 7**
Length (cm)	D7	17.7	19.2	19.8	19.0	22.0	17.0	33.0
	D8	47.5	43.0	44.2	48.0	48.0	48.0	45.0
	D9	46.7	46.5	45.8	43.0	43.0	42.0	41.0
	D10	9.8	10.4	10.1	9.0	9.0	11.0	12.0
	D11	17.5	15.5	15.2	15.0	15.0	15.0	14.0
	D12	19.4	18.6	17.9	17.0	18.0	18.0	18.0
Diameter (cm)	Head	57.0	58.0	54.0	56.0	56.0	53.0	58.0
	Shoulder	37.0	47.0	52.0	35.0	36.0	37.0	38.0
	Elbow	25.0	27.5	28.5	25.5	27.0	26.5	27.0
	Wrist	17.0	16.0	17.0	16.0	18.0	16.5	16.0
	Hip	90.0	85.5	88.5	91.0	104.0	91.0	92.0
	Knee	38.9	38.5	41.0	34.5	43.0	38.5	36.0
	Ankle	25.0	24.5	25.0	26.0	26.0	23.0	21.0
	Heel	32.0	23.0	23.0	30.5	33.0	34.0	30.0
	Metatarsus	24.0	24.0	54.0	22.0	23.5	27.5	58.0
General Informa.	Age	30	21	23	23	24	22	29
	Height (cm)	178	179	174	173	170	166	170
	Weight (kg)	70.0	74.0	76.0	70.0	80.0	69.0	64.0

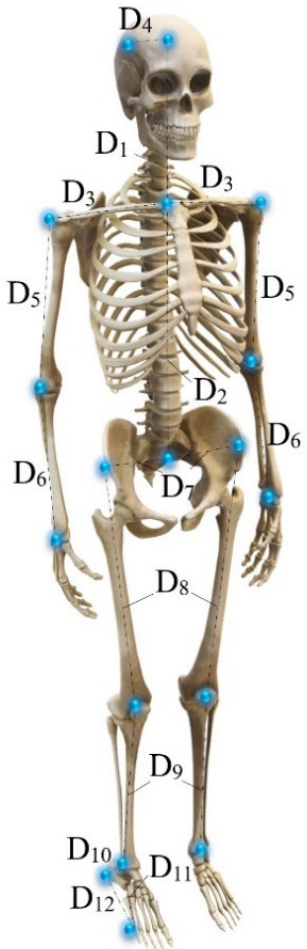

Figure 1. Schematic anthropometric information.

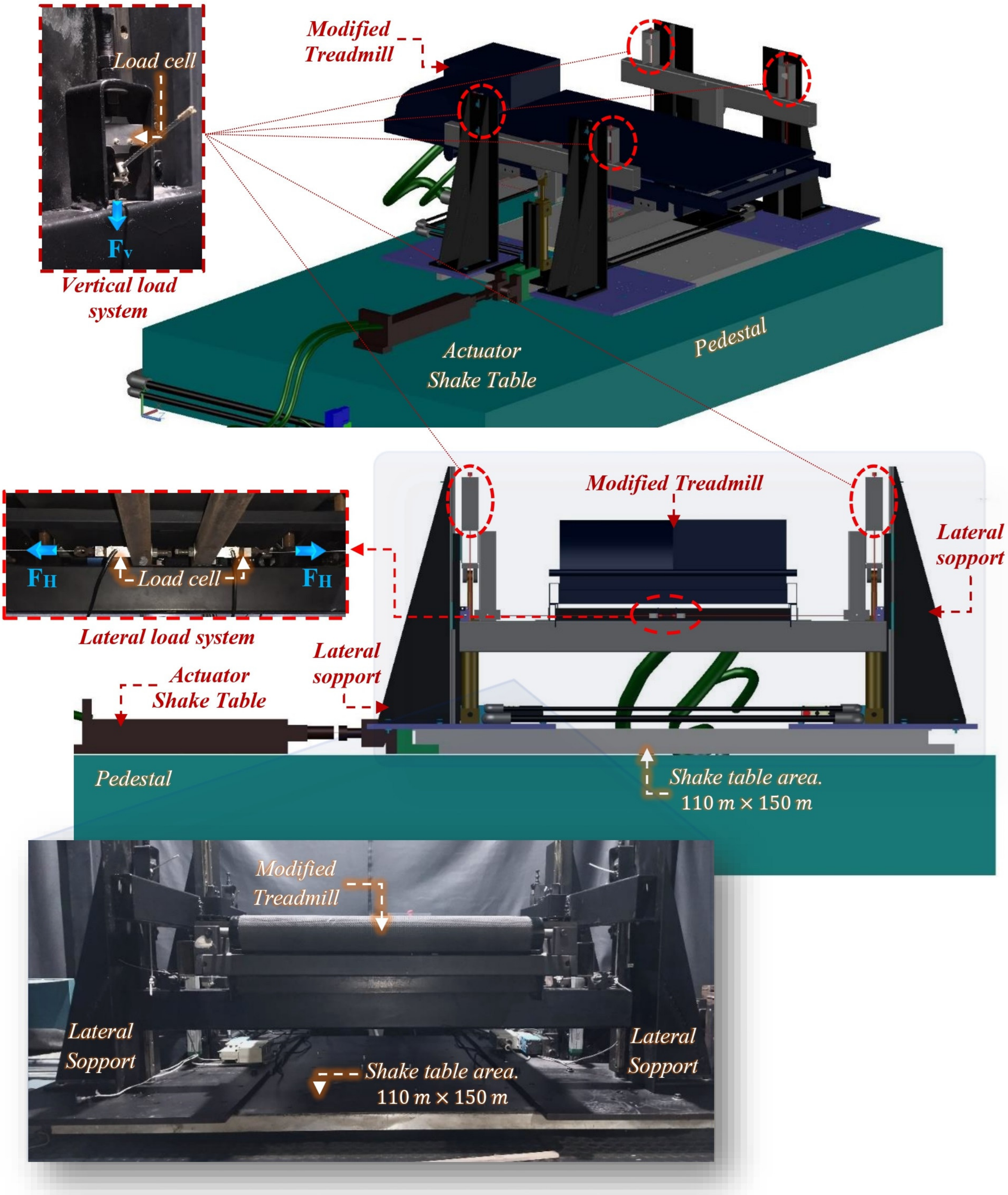

Figure 2. Human–Structure Interaction Multiaxial Test Framework: isometric view (**top**), frontal view (**middle**), real frontal view (**bottom**).

2.4. Data Collection Procedures

Experimental tests were conducted on the HSI-MTF for the STs, as shown in Figure 3. These tests involved acquiring the lateral and vertical forces induced by human gait on rigid and flexible surfaces with a sample time of 500 Hz. The human gait was performed at a constant velocity of 1.10 m·s^{-1} under lateral sinusoidal movements induced for the

HSI-MTF of 5.0, 10.0, 20.0, 30.0, and 50.0 mm, with frequencies for each displacement ranging from 0.70 to 1.30 Hz in steps of 0.10 Hz, and a duration of 30.0 s for each frequency step. In addition, a low-cost MOCAP system was implemented using smartphone devices (Xiaomi Redmi 9T (Xiaomi, Beijing, China) with 48.0 Mpx and a sampling rate of 30.0 fps) and four passive retroreflective adhesive markers with a diameter of 12.0 mm that were attached at specific points of interest: the center of mass, ankle, heel, and metatarsus (Figure 3, middle). This technology was implemented with the aim of identifying the gait cycle times and displacements in relation to the behavior of lateral loads. Before the tests, each ST carried out 2.0 min gait pre-testing at their typical gait velocity (approx. 0.90 $m \cdot s^{-1}$). Seven static tests and 245 dynamic tests were performed.

Figure 3. Experimental setup of the human gait test for ST No. 1. Isometric view (**top-left**), lateral view (**top-middle**), and top view (**top-right**). Additionally, a gait cycle (**bottom**).

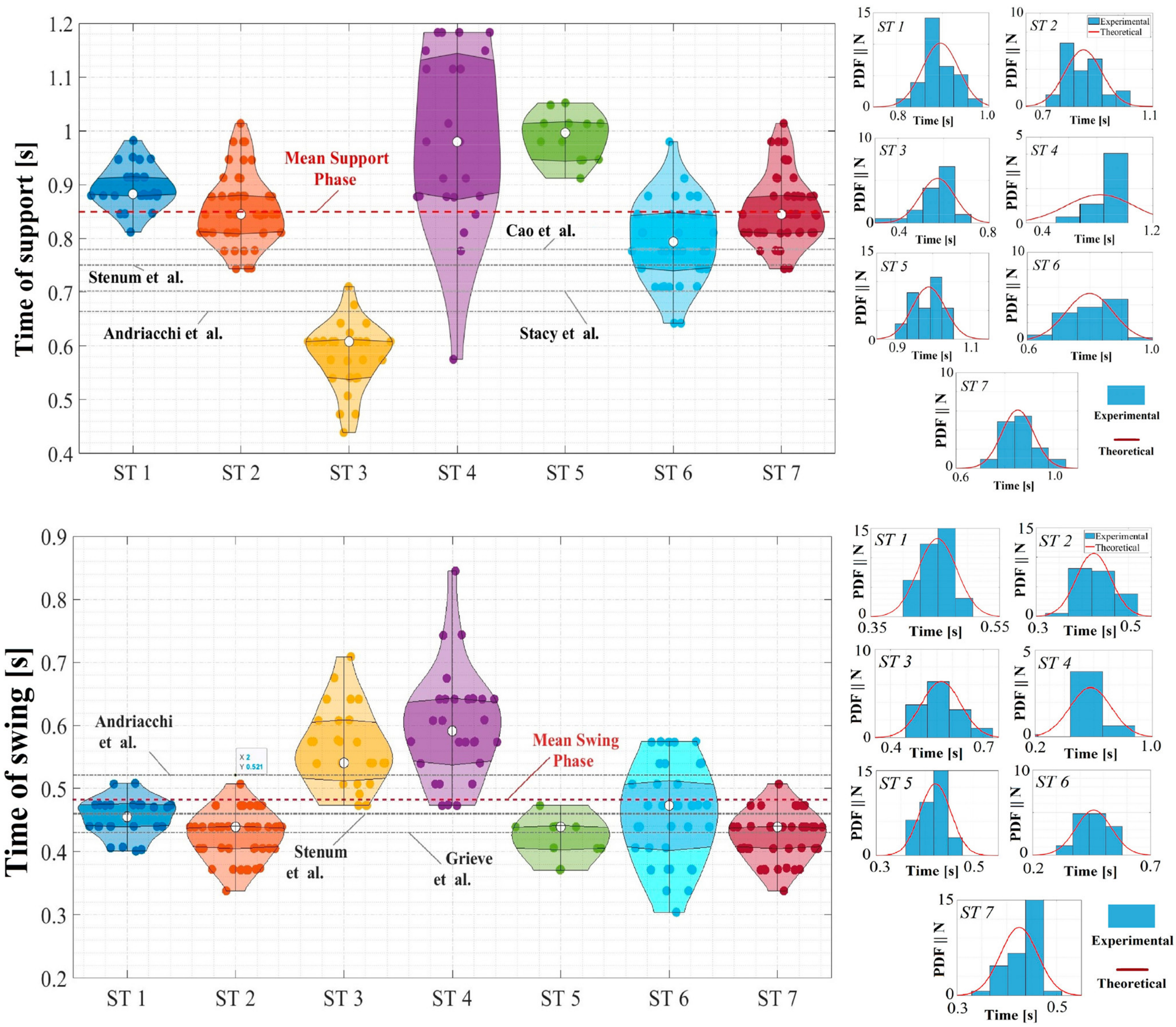

Figure 5. Statistical analysis of human gait support and swing periods; violin plot of the support phase duration and its probability density function for each subject test (**top**); and violin plot of the swing phase duration and its probability density function for each subject test (**bottom**); [51]—Grieve et al.; [52]—Andriacchi et al.; [53]—Stenum et al.; [54]—Stacy et al.; [55]—Cao et al.

The T_{su} and T_{sw} periods evaluated during human gait in the STs on the rigid surface were consistent with those presented in previous studies. Grieve et al. [69] conducted an analysis and parameterization of human gait on fifty test subjects, including both women and men. They determined that the swing time during gait was less than half of the apparent individual period, as is the case for over 70.0% of the STs studied. The parameterizations of swing time conducted on individuals with a gait speed of 1.10 m/s reported average periods of 0.43 s, deviating by 10.0% from the mean values reported in this study. In the late 1970s, Andriacchi et al. [70] conducted an experimental campaign with 70 test subjects ranging from 22 to 59 years of age, with a height of 173 $\pm$ 70 cm and weights of 757 $\pm$ 307 N. They determined support periods of 664 ms and swing periods of 521 ms for a gait speed of 1.10 m/s. According to the mean values of this research, there were overestimated swing periods by 8.0% and underestimated support periods by 22.0%. Similarly, Stenum et al. [71] reported an analysis of human gait in 32 individuals (22 males and 10 females) using a Motion Capture (MOCAP) system with pose estimation, indirectly determining support and swing periods of 0.75 $\pm$ 0.10 s and 0.46 $\pm$ 0.025 s,

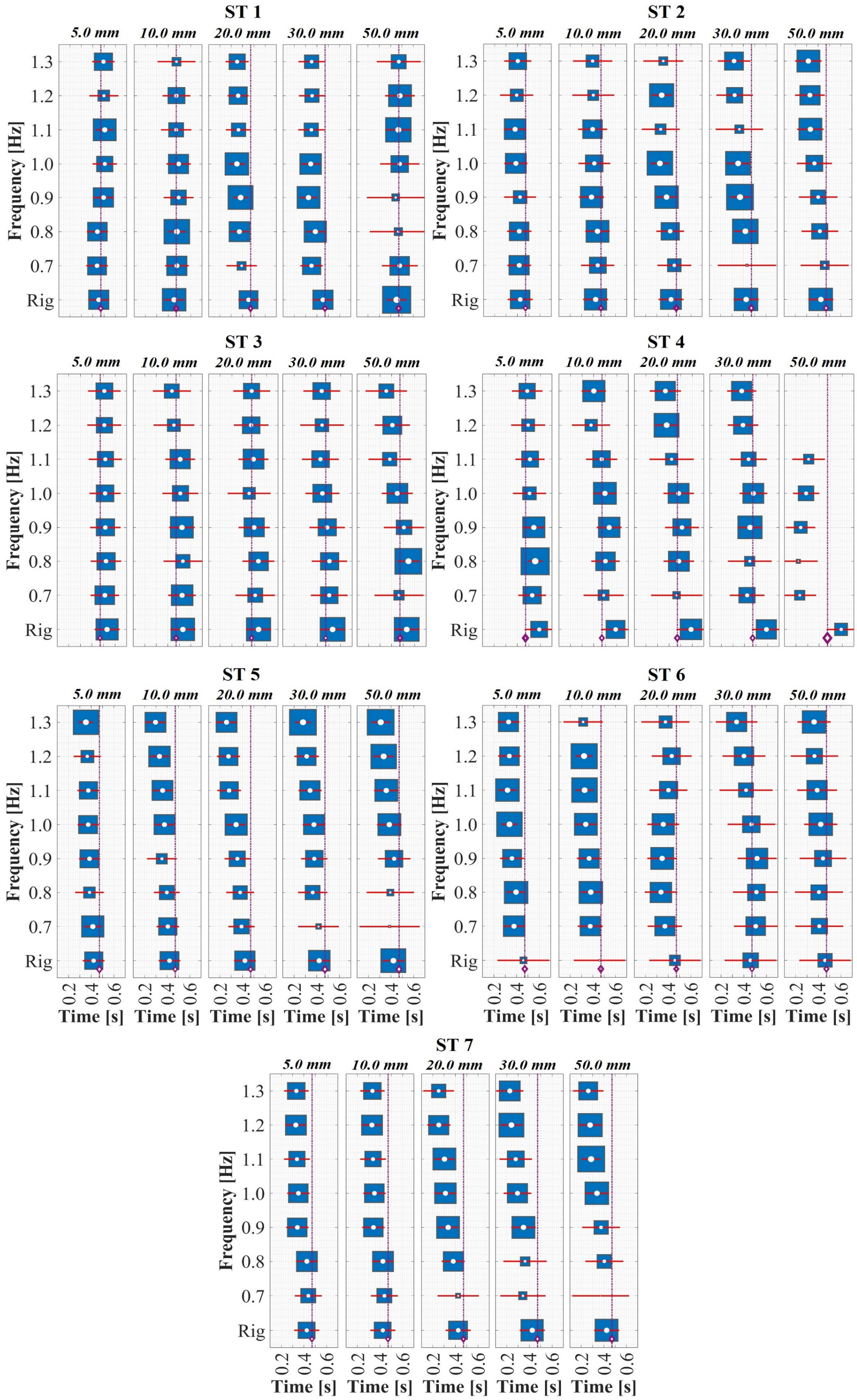

Figure 6. Support period (T_{su}) of the subject tests on multiplex harmonic surfaces.

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