Viscoelastic damper for vibration mitigation of footbridges

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Abstract. Footbridges are among long-span light-weight structures that because of their low damping ratio are susceptible to vibration. Excessive vibration in footbridges usually occurs when they are subjected to rhythmic dynamic loads caused by human activities like walking and running. In order to mitigate the human induced vibrations in footbridges, an increase in the damping ratio is often suggested as the most economical approach. Tuned mass dampers have been widely used for this purpose, however, their installation and maintenance costs are high. This has encouraged researchers to examine the efficiency of the other types of dampers. Viscoelastic dampers have been successfully employed for vibration mitigation of structures against wind and earthquake loads. However, their efficiency for reducing human induced vibration in footbridges has not been addressed. In this study, a real footbridge with a free span of 22.5 m and a width of 2.3 m was selected for numerical investigations. SAP2000 program was used to establish the finite element (FE) model of the footbridge. The established FE model was validated by comparing its natural frequencies with those measured on the field. FE model results indicated that the acceleration response of the footbridge exceeded the code specified limit. Therefore, a viscoelastic damper was designed and installed under the footbridge in order to reduce the acceleration response below the allowable level. Installation of the viscoelastic damper significantly decreased the vibrations. It was concluded that viscoelastic dampers were an economical and efficient solution for vibration problems in footbridges.

1. Introduction

Most of civil engineering structures are vulnerable to vibration problems in terms of serviceability limit states caused by dynamic loads. Footbridges are not an exception, where vibrations induced by pedestrians have a considerable impact on the dynamic response of such structures. These vibrations impact significantly human comfort and structure fatigue. Through the design process any vibration should be considered since it has a great impact on other properties of structure such as nuisance, fatigue, and strength. The most dangerous effect is the resonance phenomenon which may double the amplitude of oscillation. There are several real examples of structural failure due to vibration effects such as the Broughton Suspension Bridge in 1831[1]. Likewise, running induced vibration causes the bigger dynamic response to the footbridge. It is proven experimentally that running can easily cause the maximum acceleration of the footbridge exceeds the comfort criteria [2]. In these situations, the application of control systems can improve structural performance by reducing the vibration levels to adequate values[3]. Several active, semiactive, passive, or hybrid control systems can be adopted to achieve this aim. The control systems are classified according to their power source, the active systems require an additional power source to operate, whereas the passive systems do not require any. The semi-active systems, as their name reveals, require limited power and are normally operated by a battery. The hybrid systems are a combination of two categories of the aforementioned systems. These systems employ devices to adjust the dynamic characteristics of structures. Due to their power independency, passive devices are preferred over other types.

One of the earlier applications to enhance footbridges behavior and mitigate vibrations induced by pedestrians is the tuned liquid column damper. The efficiency tunned liquid column damper has been proved numerically and experimentally[4]. The other damper used in such cases is the tuned mass damper which is a passive damper. Many studies have shown the efficiency of this device in mitigating vibrations induced in footbridges[5]. However, due to the difficulty of installation of this device and its large mass, this device is less preferable for footbridges structures. Due to the fact that Malaysia is considered one of the largest producers of rubber in the world, the viscoelastic damper is considered an efficient and economical damping system. Hence, this paper investigates the use of a viscoelastic damper to improve the characteristics of footbridges against vibrations induced by pedestrians.

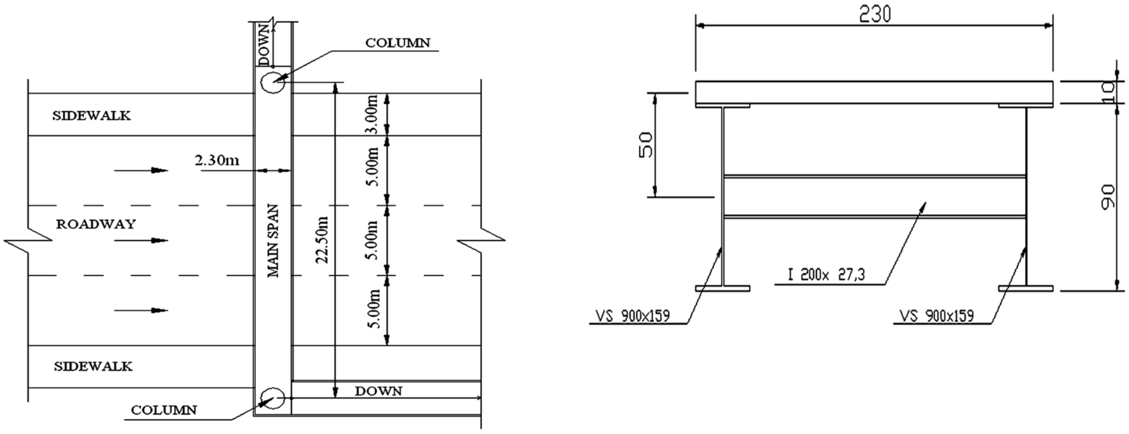
A typical viscoelastic damper employs two layers of rubber sandwiched between three layers of steel plates alternatively. When relative shear deformation takes place in the viscoelastic materials, the energy caused by dynamic loads is then dissipated. Viscoelastic dampers were used efficiently to the structural vibrations caused by different dynamic loads such as winds, earthquakes, and human activities[6]. One of the most important applications for these devices is in the twin towers of the World Trade Center building in New York City [7]. This damper also has been investigated on post-tensioned concrete bridge piers and subjected to seismic load[8]. The results revealed that a viscoelastic damper can considerably reduce the structural response and proved an additional stiffness. However, the use of viscoelastic damper in footbridges has not been investigated. Consequently, this research is keen to inspect the efficiency of the viscoelastic damper in absorbing vibrations developed in footbridge structures. The research considered a numerical approach to investigate this configuration using SAP2000 software. Two sources of vibration have been considered to be examined, specifically by human walking and running. The damper effect is measured in terms of maximum displacement and accelerations developed according to the loading scenarios.

2. Methodology

The research procedure for this research consists of four main steps. Firstly, validate the simulated finite element model of the proposed footbridge. The second step included a specification for the load cases. Before incorporating the viscoelastic damper into the model, the damper model will be validated in the third step. Lastly, different configurations were considered to optimize the number and locations of dampers for the proposed system.

2.1. Model of the footbridge

The suggested footbridge to be simulated as a reference structure is similar to the footbridge used in previous research[9][10]. The model characterizes a real footbridge situated in Rio de Janeiro, Brazil. The bridge is 22.5 m in length and its width is 2.3 m. The bridge mainly consists of a reinforced concrete floor of 100 mm thickness supported by two welded wide flanges (900mm*159mm) along its length and simply supported at its ends by columns. Transverse beams are fastened between the longitudinal steel beams. The beams were with I section and dimensions of (200mm* 27.3mm). The steel sections have properties of 300 MPa yield strength and the compressive strength and Young's modulus of the slab is 30 MPa and 3.84 x 104 MPa respectively. The schematic view of the footbridge is presented in Figure 1. In order to define the damping ratio of the system, 2% was considered as recommended damping ratio of composite footbridges by previous research [11]. Using SAP2000 all models have been simulated to be analyzed. The simulated footbridge is presented in Figure 2. The validation of models was through a comparison between the natural frequency of the model and previous values obtained from researches [9][10]. The simulated footbridge showed a 5.4 Hz natural frequency for the first mode of vibration which is 97 % identic compared to the original footbridge has a 5.5 Hz natural frequency, consequently the model is eligible for further studies.



(a) (b)

Figure 1. Dimensions of footbridge model: (a) Top view and (b) Cross-section (dimensions in cm).

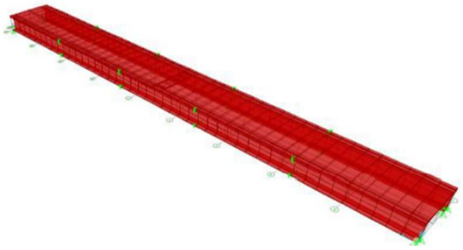


Figure 2. Footbridge model simulated in SAP2000.

2.2. Loading scenarios

In order to inspect the behavior of the proposed system extensively, three loading scenarios have been investigated based on previous studies correlated with footbridge vibrations[12], The first loading scenario is normal walking which is represented by a periodic dynamic force with frequency analogous to the natural frequency of the footbridge to cause the resonance effect. According to previous researches, the pedestrian load can be represented as a combination of three components, hence the applied frequency load should be divided by 3.
as presented below:

i. Load Scenario I (Walking I)
The load is applied harmonically with frequency of 5.4 Hz (as shown in Figure 3) in the middle span of the footbridge.

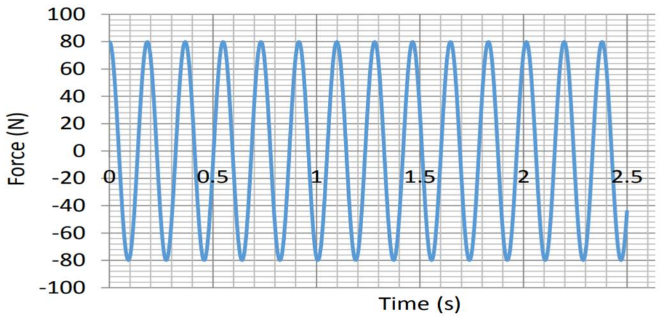


Figure 3. Loading scenario I.

ii. Loading Scenario II (Walking II)
As presented in the previous studies, the walking model should also contain the weight of the pedestrian, hence the second loading scenario is a combination of the weight of the pedestrian as a static part and harmonic forces represented by the Fourier series. The loading frequency is also 5.4 Hz, as shown in Figure 4.

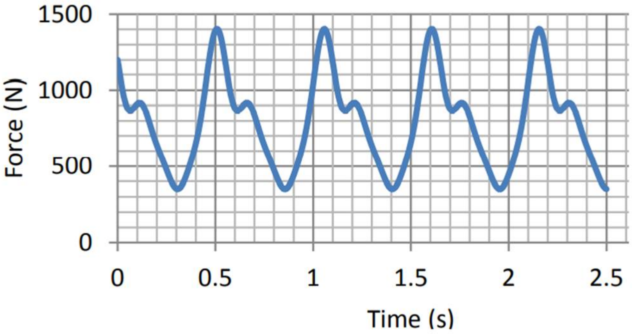


Figure 4. Loading scenario II.

iii. Loading Scenario III (Running)
The schematic representation of this loading case is shown in Figure 5. To simulate running scenario, two harmonics with the frequency of 2.7H should be applied (2*2.7 =5.4Hz). It consists of static part which is caused by pedestrian weight and dynamic load represented by Fourier series based on a time-domain repeated force, as presented in Figure 5.

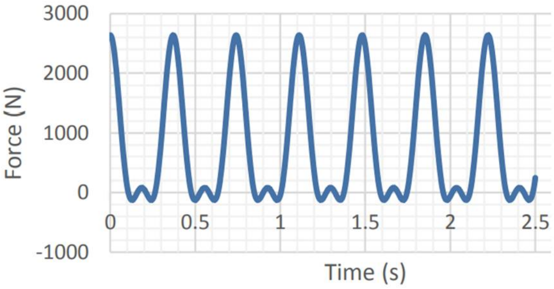


Figure 5. Load scenario III.

2.3. Model of the viscoelastic damper

After the validation of the model of the footbridge, the next step is to validate the damper model. The damper model was simulated based on data experimentally extracted by a previous study [13]. The viscoelastic damper employs two layers of rubber with are of 1200mm^2 (60mm*20mm) and a thickness of 5 mm for both layers, as depicted in Figure 6. Using a dynamic shear test the response of the damper has been investigated. The results extracted are represented by the hysteresis loop as shown in Figure 7b.

Commercial software provides several models to simulate different types of dampers. Studies showed that a numerical model of a viscoelastic damper could be achieved using two elements which are linear spring and dashpot element linked in parallel, which is defined also as the Kelvin model as depicted in Figure 7a[14]. The spring element represents the elastic property of the damper and the dashpot element represents the damping property of the damper. The hysteresis produced by the model and compared to the experimental curve is presented in Figure 7b. As shown in the comparison, there is a good match between the results consequently validating the model for further studies.

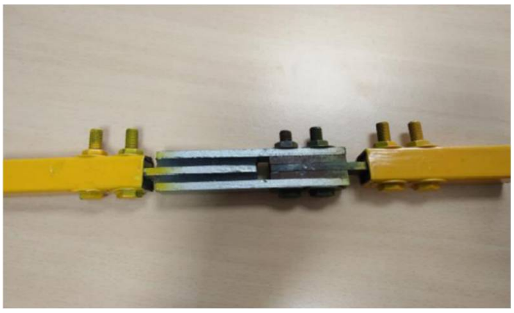
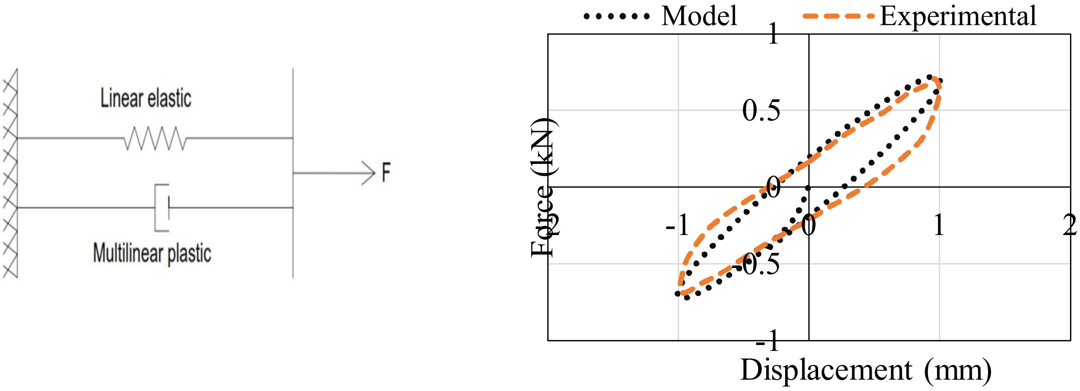


Figure 6. Experimentally tested viscoelastic damper[13].



(a) (b)

Figure 7. Proposed model for the dampers and the verification: (a) Physical model and (b) Model verification.

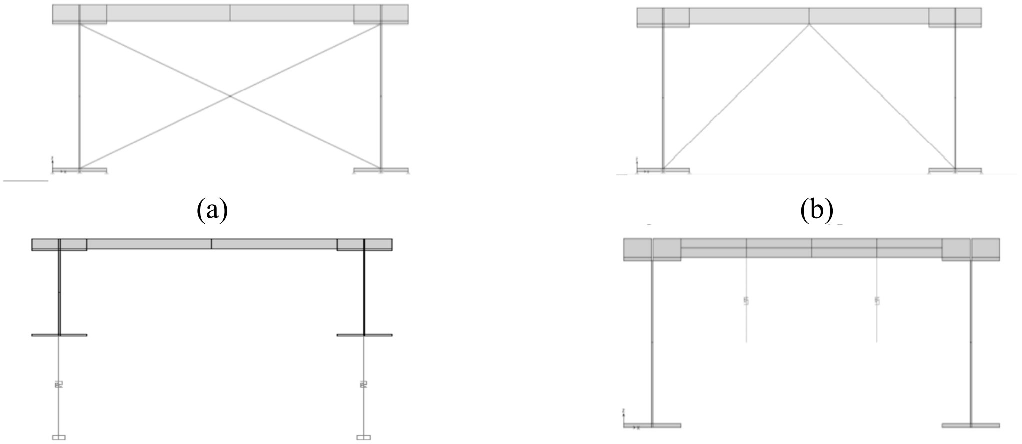
To optimize performance of viscoelastic dampers in footbridges, four configurations have been proposed to be investigated, as detailed in Figure 8.

a. Two directions brace (X) spaced 2.5 m in length (see Figure 8a).
b. Inverted V configuration and spaced 2.5 m in length. (see Figure 8b).
c. Provide an additional beam under the girder and attach dampers between the girder and the beam with spacing 0.5 m, 1.5m, and 2.5m from the end of the bridge (see Figure 8c)
d. Dampers vertically under the concrete deck at the middle of the bridge, connected by post tension cable to the I-beam at the end of the bridge. (See Figure 8d).

3. Results and discussion

The main objective of this study is to inspect the efficiency of the viscoelastic damper in footbridges. Several configurations and locations have been investigated to provide desirable damping to the system. The desired limitations for any system is specified by standards, where the “ International Standard Organization” ISO 2631-2 [15] specifies the limit values for peak acceleration as 5 % g. Furthermore “AASHTO LRFD “ [16] specify maximum deflection in the mid-span as less than the length of the span divided by 1000 (L/1000). Hence, the results of the proposed system are assessed in terms of maximum values of acceleration and deflection. It is noteworthy to mention that the span length of the footbridge is 22.5 m, thus the maximum deflection is 22.5 mm.

Results of the analysis are summarized in Figure 9, for each loading scenario and configurations of dampers. The results comprised values of maximum acceleration and deflection for each case. In general, the footbridge is within the allowable values of peak acceleration and displacement for the walking scenario I and II. Whereas, in the third loading scenario (Running case), the footbridge exceeds the allowable limits, as presented in Figure 9, where the peak acceleration of the footbridge is 6.5g at resonance. It can be clearly seen that use of a viscoelastic damper has a noticeable effect on the dynamic response of the system considerably. However, configurations X and inverted V showed less efficiency than other configurations in reducing the peak of acceleration. This is mainly because braces provide an additional stiffness against lateral movement, while the vibrations, in this case, are transited vertically.



(a) (b)

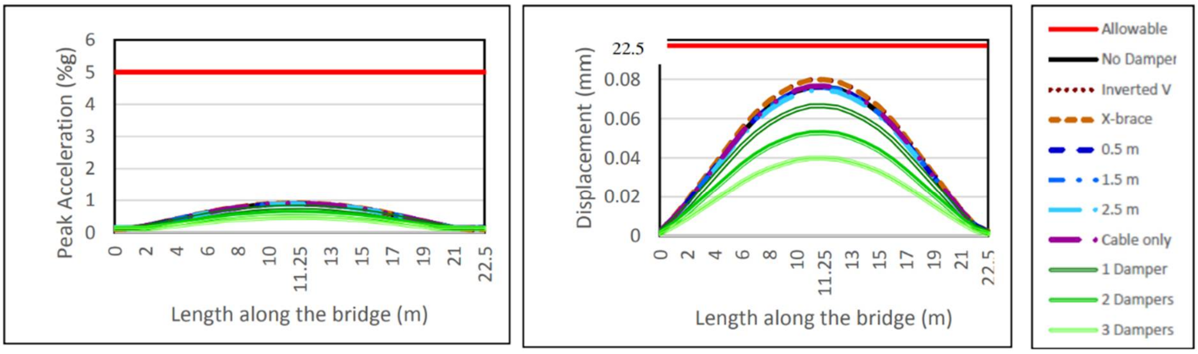
(c) (d)

Figure 8. Proposed configurations for the dampers: (a) X-brace type of connection; (b) Inverted V type of connection; (c) Vertically under the girder, distance from bridge end and (d) Vertically under the deck at the middle of the bridge.

Vertical dampers distributed horizontally showed an observable enhancement to the footbridge. The dampers were distributed at distances 0.5, 1.5 m, and 2.5 m. It is clearly shown that as the damper nearer the mid-span the more efficient response was achieved with the least peak acceleration. This is due to the fact that the mid-span has the largest deflection, consequently, a higher stiffness and damping would be developed in the damper[17]. However, the steel beams may obstruct traffic movement beneath the footbridge, hence the damper can only be placed a maximum of 3 m from the end of the footbridge.

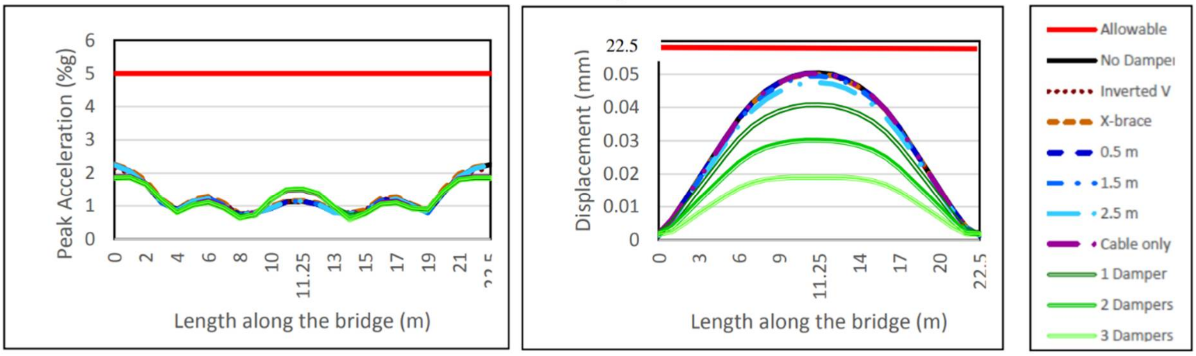
In order to avoid disturbing traffic, the damper can be connected to the footbridge along its length using a post tension cable attached to the columns at the ends of the footbridge. Dampers are connected vertically between the cable and the concrete deck. One cable is sufficient to support the dampers, however additional transverse beam should be provided to connect the double columns at the ends of the bridge. Then the cable is attached to the center of the transverse beams. In order to investigate the effect of the cable solely, an additional case was analyzed. The cable only case showed insignificant improvement in behavior of the footbridge, as depicted in Figure 9. However, by utilizing dampers in this configuration a noticeable reduction was achieved in peak acceleration and deflection. For further investigation, the effect of number dampers on this configuration was also established. Three cases were investigated, one, two, and three dampers. Using one damper connected to the cable showed less efficiency than in other cases. Whereas, the use of two and three dampers showed a significant reduction in peak acceleration and displacement. Consequently, at least two dampers should be provided to achieve the required reduction in the dynamic response of a footbridge.

To sum up, adding dampers to the footbridge has less effect on displacement responses in all cases. Contrariwise, viscoelastic dampers improved dynamic responses of the footbridge significantly in terms of peak acceleration. Also, it is noteworthy to mention, that not all configurations of the proposed system showed an advantageous response specifically the X and V bracing. On other hand, connecting dampers to the footbridge showed a promising reduction in response. Furthermore, a number of dampers affects substantially the suggested configuration.



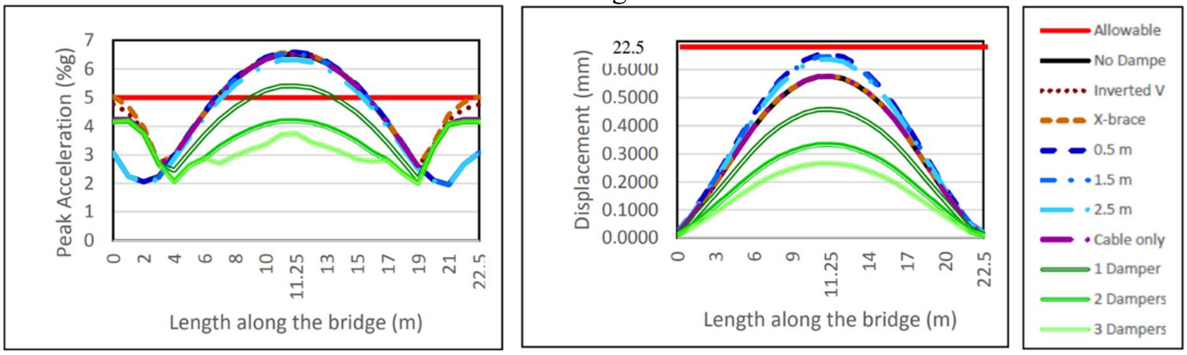
(a) (b)

Walking I



(a) (b)

Walking II



(a) (b)

Running

Figure 9: Graph of peak acceleration (a), and displacement (b) against length along the bridge for load models

4. Conclusions

In this research, the use of a viscoelastic damper as an alternative to mitigate vibration induced by pedestrians in footbridges, is investigated numerically using structural analysis software SAP2000. The findings obtained from this study are summarized as follows:

1. Normal walking causes fewer dynamic forces and vibration problems compared to the running loading scenario in footbridges.
2. Providing a viscoelastic damper as an energy dissipator with footbridges reduce the dynamic response of such structures significantly.
3. Different configurations could be considered to facilitate viscoelastic damper in footbridge structures. However, the most efficient configuration is when the damper is installed vertically

and parallel to the deflection direction. Furthermore, as the damper is installed near the maximum deflection, the more efficient damper to mitigate vibration induced.

4. Number of installed dampers has a significant influence on the efficiency of the damper system. At least two viscoelastic dampers should be installed under the concrete deck to provide the anticipated damping level.

Consequently, the viscoelastic damper is considered as an economical alternative for other types of dampers to be used in Malaysia as it is cheaper and can function efficiently too.

5. References

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