THE EFFECT OF STIFFENING OF FULLY COMPOSITE MODULAR FOOTBRIDGE ON HORIZONTAL LOADS

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Abstract

In the design of the footbridge structure, horizontal loads, primarily from wind effects, cannot be overlooked. During the research of the fully composite modular footbridge, low horizontal stiffness was revealed, which was significantly affected by the connection points. Horizontal stiffness is mainly controlled by the joint plates at the module connections, and therefore, horizontal stiffening in the plane of the cross members was proposed. The stiffening adheres to the modular system and does not interfere with the assembly of the footbridge for the required span. The different stiffness of the footbridge in the horizontal plane without and with the use of horizontal bracing was experimentally verified.

Keywords

Fully composite modular footbridge, horizontal loads test, effect of stiffening

1 INTRODUCTION

As part of a collaborative project between Brno University of Technology, Faculty of Civil Engineering, and the company PREFA KOMPOZITY, a.s., a fully composite modular footbridge has been developed in accordance with the Prospect for new guidance in the design of FRP: support to the implementation, harmonization and further development of the Eurocodes [1]. This footbridge is intended to serve as a temporary structure. The modular design, in conjunction with the use of fibre reinforced polymers, enables fast and easy construction, allowing for the adjustment of the bridge span according to the number of modules. The length of the basic module is 2.0 meters, with a free width of 2.5 meters.

At the end of 2022, experimental verification of the load-bearing capacity and vertical stiffness was conducted on a full-scale test sample of a footbridge with a span of 8.0 meters (consisting of four modules) as shown in Fig. 1. The footbridge was incrementally loaded in the vertical plane according to ČSN 73 6209 [2]. The experiment demonstrated sufficient vertical stiffness and load-bearing capacity of the structure, even at approximately 140% of the designed load (5.0 kN/m^2 according to ČSN EN 1991-2 [3]). Significant observations included compression occurring at the module joints, resulting in permanent deformations. This aspect had to be considered in the numerical model, which, even before adjustment, exhibited very good agreement with experimental measurements.

Fig. 1 Fully composite modular footbridge with a span of 8.0 meters.

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For the safe and comfortable use of the footbridge, it is crucial for the structure to reliably withstand horizontal loading effects acting perpendicular to the wall beams (guardrails). Therefore, the goal of the research project FAST-J-23-8343 and FW06010649 was to investigate the impact of stiffening on the horizontal stiffness of the structure and further refine the numerical model of the developed fully composite modular footbridge. The construction of the footbridge from individual modules significantly determines its horizontal stiffness, primarily influenced by the connection plates at the point of contact of the modules. This was evident during assembly and vertical load testing, where low or insufficient stiffness in the horizontal direction was identified. To increase horizontal stiffness in the plane of the crossbeams, stiffening with rectifiable bracing in a cross shape was designed. This solution respects the modular system to maintain the concept of adjusting the span according to current needs. The horizontal bracing is designed using stainless steel cables and other readily available steel components (see Fig. 2), allowing for flexible activation of stiffening as needed.

Fig. 2 Anchoring and Rectification of horizontal bracing.

2 METHODOLOGY

Numerical model

According to the standards ČSN EN 1991-1-4 [4], Technical Specifications TP 258 [5], and ČSN EN 1991-2 [3], the guardrails of the footbridge construction must safely transmit the specified horizontal loading effects. Additionally, it is necessary to consider the maximum allowable horizontal deformation:

- Horizontal traffic loading according to Technical Specifications [5], linear loading with a horizontal action value of $q_{hk} = 1.2$ kN/m.
- Wind loading according to Technical Specifications [5], surface loading acting perpendicular to the guardrail with a value of $F_w = 0.8$ kN/m^2.
- Snow loading according to Technical Specifications [5], surface loading acting perpendicular to the guardrail with a value of $S_n = 1.0$ kN/m^2.
- Wind loading according to ČSN EN 1991-1-4 [4], where the magnitude of the loading depends on the actual location of the footbridge and can be reliably determined only after this information is known.
- Maximum horizontal deformation of L/250.

Each loading condition was introduced into the numerical model of the fully composite footbridge as loading states, and from these, extremes were subsequently identified on the solved footbridge. In the numerical model, horizontal stiffness was controlled only by joints allowing rotation in all directions, as depicted in Fig. 3 a), in the upper and lower flange of the wall beam. The stiffness was defined only in the longitudinal and horizontal directions of the footbridge. These joints represented the real implementation of connections between individual footbridge modules, created using connection plates.

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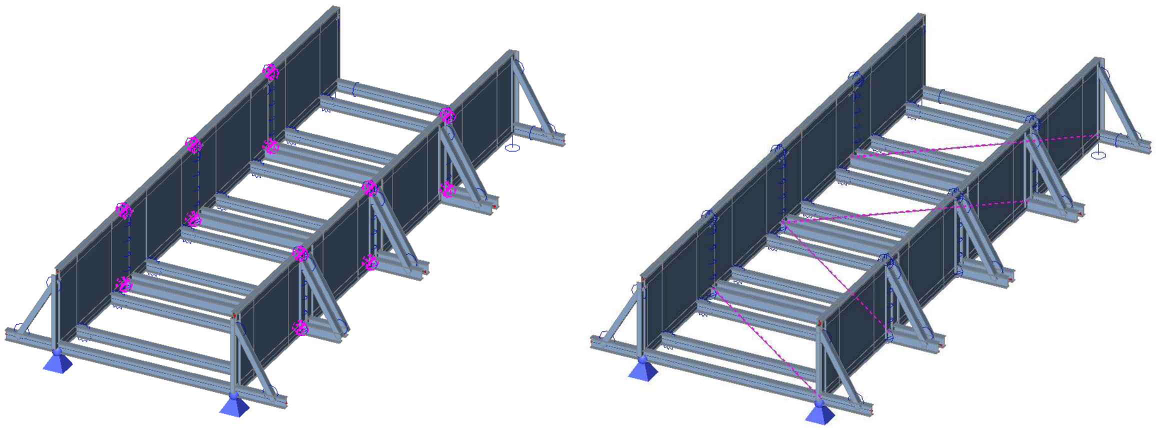
Tab. 1 presents the resulting horizontal deformations of the footbridge for individual loading conditions. In the case of the unstiffened modular footbridge, the limit deformations were exceeded for all specified types of loading. For this reason, horizontal bracing was proposed in the form of steel cables placed at the level of the crossbeams. The goal was to design bracing that respects the modular system (so that the ability to chain individual modules is not restricted) and uses readily available elements. The choice of stiffening (see Fig. 3 b), stainless steel cable with a diameter of 5.0 mm and a strength of 1570 MPa, was optimized based on the deformation magnitude and the internal forces generated in the cable.



a) highlighted joints controlling the horizontal stiffness.

b) highlighted steel cables.

Fig. 3 Numerical model of the fully composite modular footbridge.

Similarly, to the case of the unstiffened footbridge model, the loading was introduced into the model stiffened with steel cables. Tab. 1 clearly shows that the addition of stiffening had a favourable effect on horizontal deformations. With the addition of bracing, horizontal deformations were approximately 6.1 to 9.0 times smaller depending on the type of loading.

To verify the functionality of the proposed stiffening and the overall behaviour of the footbridge, a full-scale experiment was conducted. Due to the dimensions of the fully composite modular footbridge (length 8.0 m), it was not feasible to apply uniform horizontal loading. Therefore, loading conditions were modeled where an isolated horizontal force (1.0 and 3.0 kN) acted at the midpoint of the beam span.

Tab. 1 Horizontal deformations of numerical models under various loading conditions according to Technical Specifications [5].

		Horizontal by TP [5]	**Wind by TP [5]**	**Snow by TP [5]**	**Limit**	**Experiment 1.0**	**Experiment 3.0**
		1.2 kN/m	*0.8 kN/m²*	*1.0 kN/m²*	*L/250*	*1.0 kN*	*3.0 kN*
Hor. def. [mm]	**Unstiffened**	*64.0*	*50.83*	*63.54*	*32.0*	*11.72*	*35.16*
	Stiffened	*8.0*	*8.05*	*10.06*		*1.30*	*3.91*
Effect of stiffening		*8.0*	*6.13*	*6.32*		*9.02*	*8.99*

Preparation of the experiment

The verification of horizontal stiffening was conducted in the AdMaS research centre area, where the test sample of the footbridge was supported on concrete blocks. The loading itself, with a point force at the midpoint in the horizontal stiffening level (or crossbeams), was achieved using a tension hydraulic press with a counterweight (vehicle, see Fig. 4). The loading level was chosen to monitor the impact of stiffening on horizontal deformations of the footbridge. The loading test served to verify the functionality of the bracing in different states of stiffening activation. For a comprehensive description of the footbridge behaviour during the loading test, a total of 22 sensors were installed. Out of these, 19 sensors measured displacements in the horizontal direction, placed near the stiffening frames (junction points of individual modules) on the upper and lower flanges. One sensor recorded the magnitude of the applied load, and the remaining two sensors monitored vertical displacements of the stiffening frame, i.e., the inclination of the footbridge. The right side of the footbridge (the location of the applied force) was monitored more, while the left side served to check for symmetry.

The test verified the functionality of the stiffening, and for this reason, the stiffening variants always started from the same point (zero horizontal deformation). The loading was carried out in steps, with an incremental force of 1.0 kN, followed by a delay to stabilize deformations according to ČSN 73 6209 [2]. The course of the loading test is depicted in Fig. 5. The maximum achieved force varied depending on the configuration of the horizontal stiffening in the footbridge. In total, four variants of horizontal stiffening for the footbridge were tested:

- Stiffened 1: bracing activated with "human force".
- Partially Stiffened: the stiffening cables were initially in an unloaded state, but remained anchored at the anchoring points.
- Unstiffened: stiffening cables were removed.
- Stiffened 2: bracing activated with "human force" to verify the behaviour.

Fig. 4 View of the loading test with the applied force in the horizontal direction.

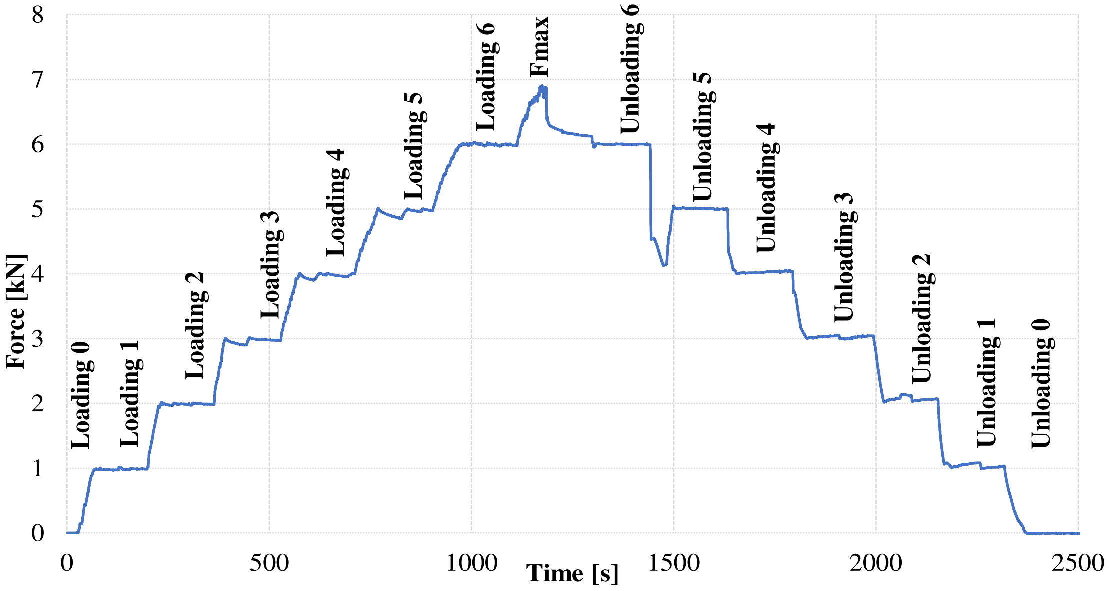


Fig. 5 Course of the loading test, increment of force over time.

3 RESULTS

Due to the extent of the text and the amount of measured data from the experiment, the results are presented in more detail only for one of the variants of horizontal stiffening. In other cases, attention is drawn to different behavior from the other types of stiffening. All data is kept by the main author of the article. The monitored deformations for experimentally verified stiffening configurations are summarized in Tab. 2.

For better reference , individual measurement points are marked in Fig. 6, including an example description and subsequent explanation of the measured point:

- Stiff. Frame 2.1. Low R – 2.1. = the first stiffening frame on the second module of the footbridge, Low R= lower flange on the right side of the footbridge.
- Stiff. Frame 4.2. Upp. L – 4.2. = the second stiffening frame on the fourth module of the footbridge, Upp. L = upper flange on the left side of the footbridge.

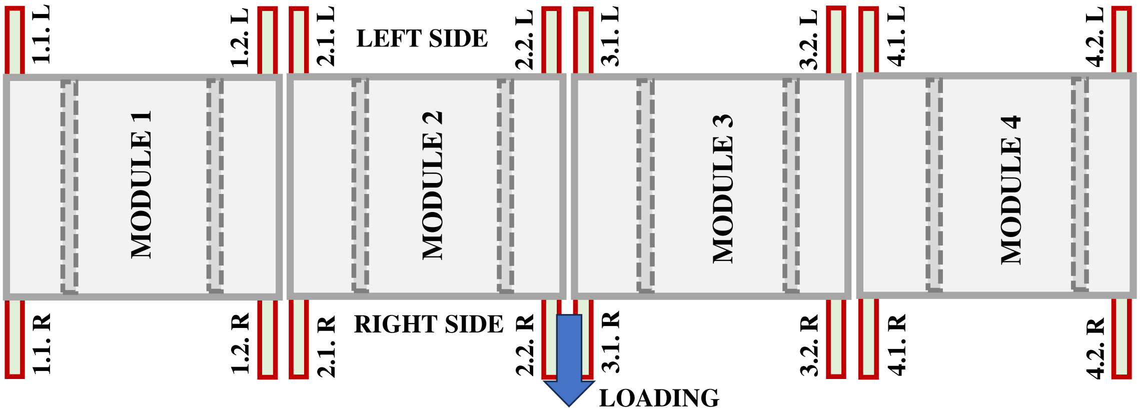


Fig. 6 Designation of measured points on the footbridge.

Variant 1: Stiffened 1

In the case of the Variant 1, a maximum force of approximately 6.91 kN was achieved, at which point the counterweight (vehicle) began to shift. The maximum force corresponded to a deformation at the lower flange in the middle of the bridge span of approximately 21.2 mm. As shown in Fig. 7, the increase in horizontal deformation did not exhibit a completely linear relationship, which was caused by compression in the joints between individual modules and inaccuracies in the execution. An important finding was that permanent deformations remained on the bridge after complete unloading. Approximately in the middle of the bridge span (Stiff. Frame 2.2. Low R), a horizontal deformation of approximately 3.74 mm was measured during the unloading state Unloading 0.

From Fig. 8, it can be stated that the deformations of the bottom flange on the right side were identical to the deformations on the left side, confirming the symmetry of the structure. Within the length, visibly lower deformations are observed on the first half of the bridge (modules 1 and 2). This could be caused by uneven tensioning of the steel cables. For the upper flange, it was found that small differences between the right and left sides occurred with increasing force (approximately 0.5 mm difference at 6.0 kN).

These facts are also illustrated in Fig. 9, where it is possible to see the inclination of the wall beam, which was primarily impacted by the stiffness of the stiffening frames.

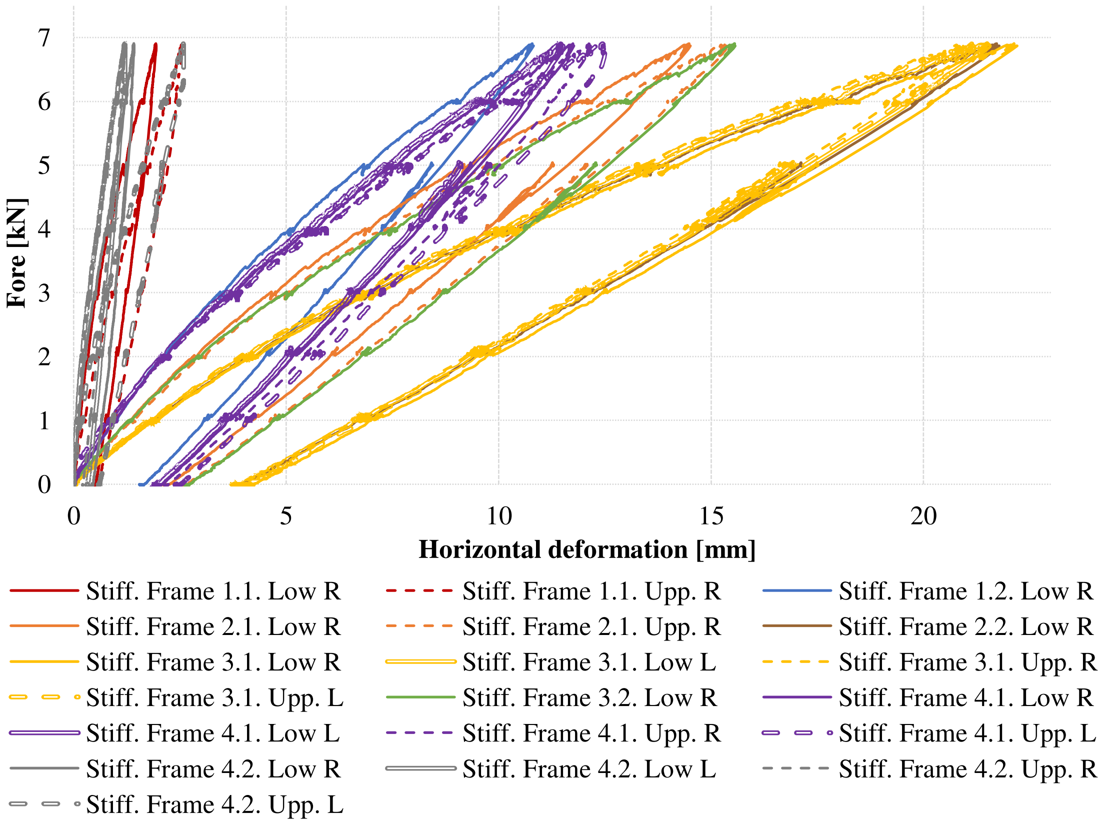


Fig. 7 Increment of horizontal deformation of the footbridge depending on the applied load, Variant 1.

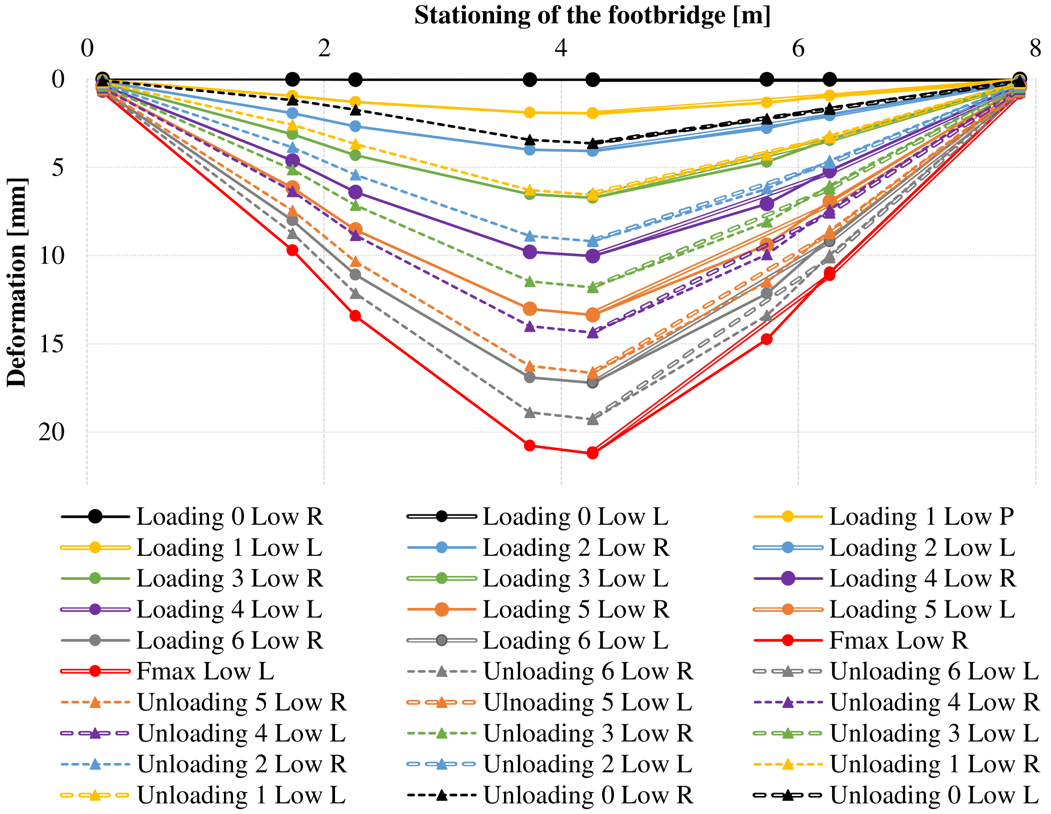


Fig. 8 Horizontal deformation of the footbridge measured on the lower flange during the load test, Variant 1.

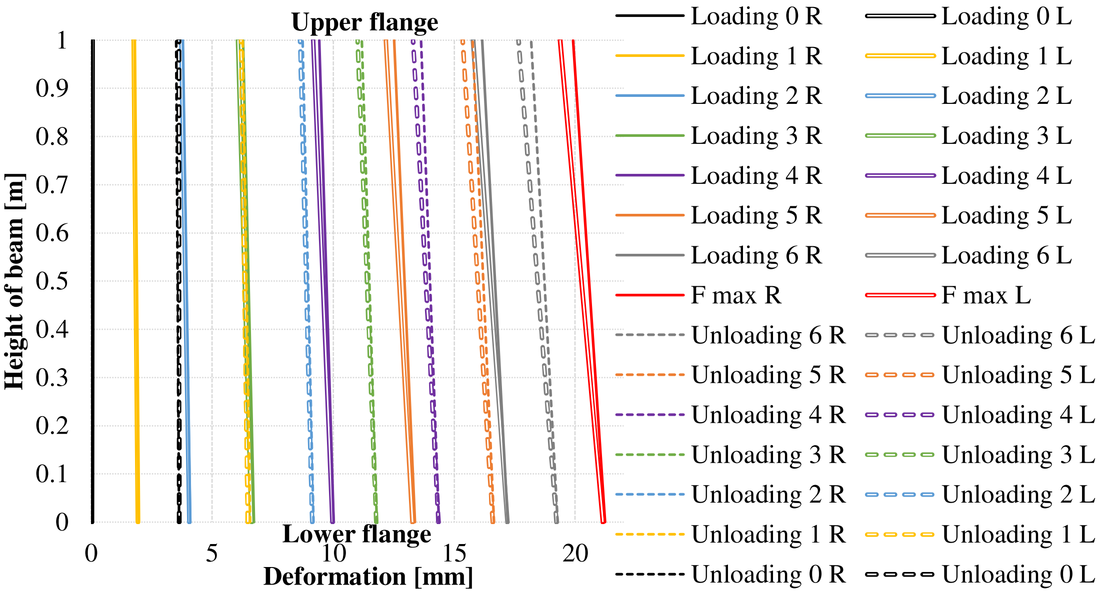


Fig. 9 Comparison of deformations at the measured location Stiff. Frame 3.1, Variant1.

Variant 2: Partially Stiffened

In the case of the second type, a force of approximately 6.0 kN was achieved, corresponding to a horizontal deformation at the bottom rail of approximately 52.15 mm. The overall global behaviour of the footbridge was like the first variant (Variant 1). A significant difference occurred in the activation of the bracing, as shown in Fig. 10, where there is a noticeable change in the trend within the range of 2.0 to 3.0 kN. At this point, the horizontal stiffening was activated, which was significantly sagging (inactive) before the start of loading.

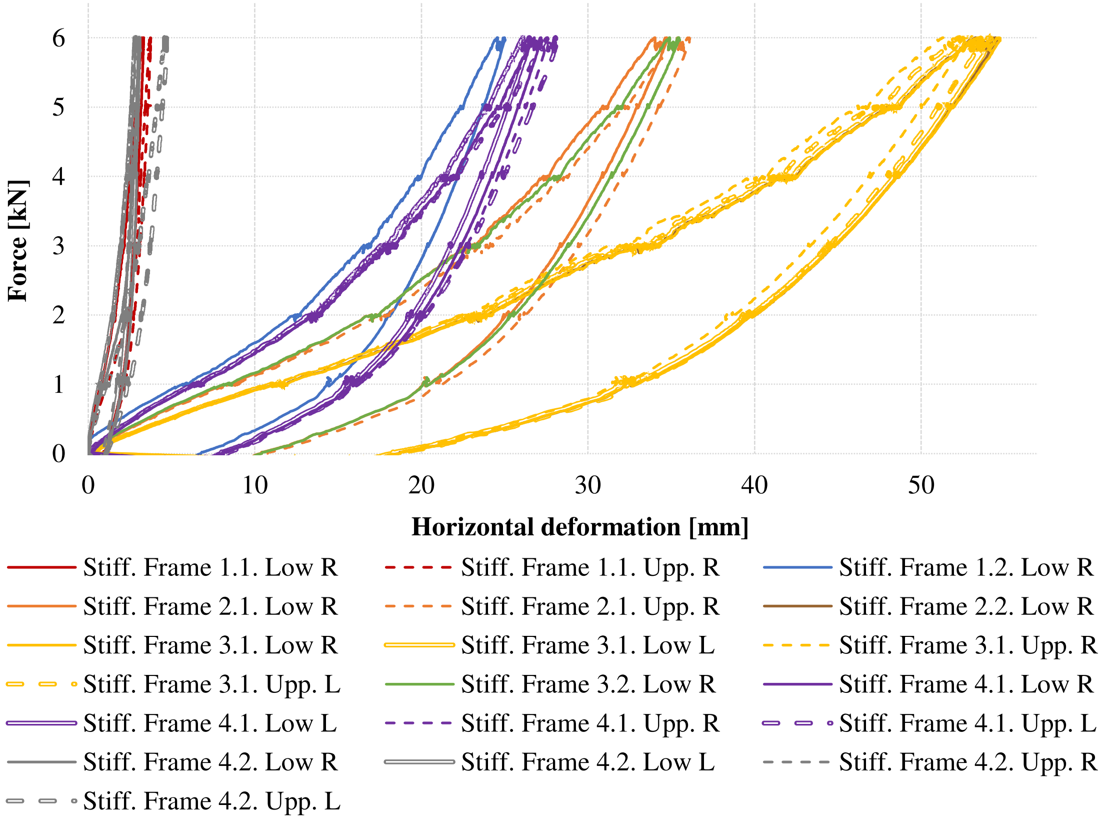


Fig. 10 Increase in the horizontal deformation of the footbridge depending on the applied load.

Variant 3: Unstiffened

In the loading configuration of Stiffening Variant 3, where the steel stiffening providing stiffening was completely dismantled, a maximum force of approximately 3.6 kN was achieved due to the maximum extension of the loading cylinder. At the highest load, a horizontal deformation of approximately 58.3 mm was measured. The stiffness depended solely on the joint plates, and the relationship was completely linear. Horizontal deformations in the longitudinal direction were entirely symmetrical, and, as in previous cases, the behaviour was identical on both sides at the bottom flange. Even in this case, permanent deformations remained after unloading the structure.

Variant 4: Stiffened

Before the last configuration of the test, horizontal bracing was again activated with a “human” force, which, however, differed from the Variant 1 configuration (manual tightening without measuring the tightening torque did not allow identical stiffening activation conditions). The maximum force achieved in this configuration was approximately 6.01 kN, corresponding to a deformation in the middle of the span on the bottom flange of the right beam of 12.66 mm. Fig. 11 illustrates that the stiffening of Module 1 was significantly higher than in the other modules, causing different behaviour from previous stiffening configurations. In this case, different horizontal deformations were observed not only on the top flange but also on the bottom flange. Like previous configurations, permanent deformations remained under the unloading of the structure.

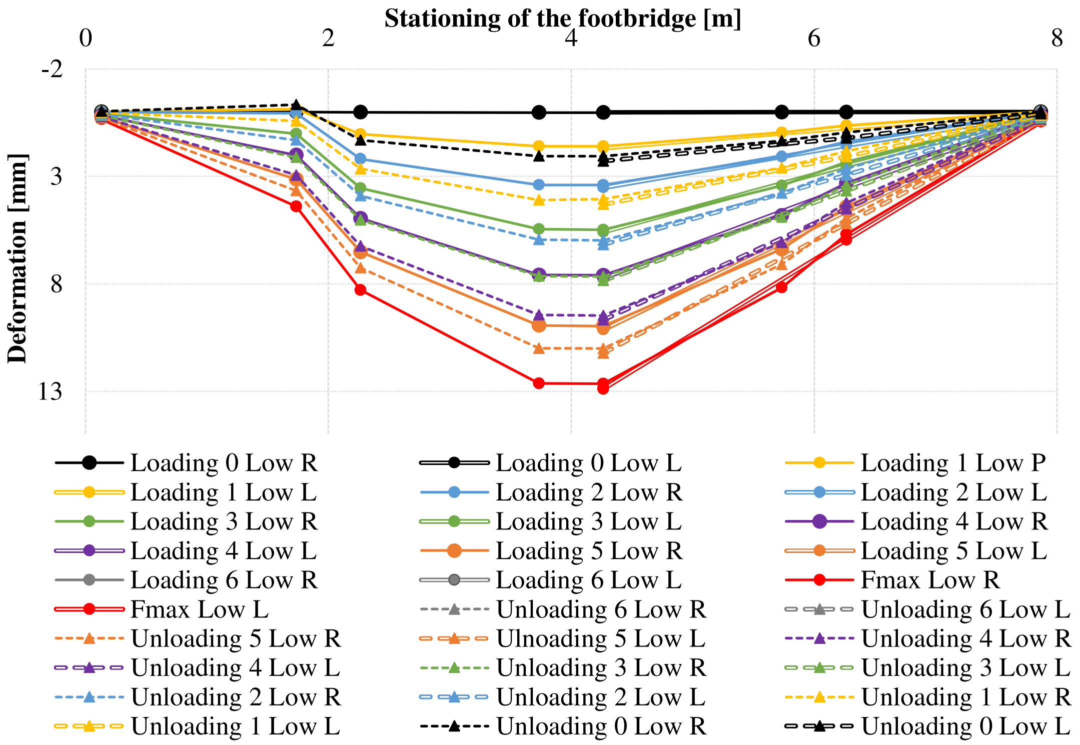


Fig. 11 Horizontal deformation of the footbridge measured on the lower flange during the load test, Variant 4.

An overview of horizontal deformations on the right side of the footbridge at the lower flange is summarized in Tab. 2. Only selected load levels were chosen based on the maximum achieved forces in individual stiffening configurations.

The evaluation of measured horizontal deformations confirmed the favourable effect of the proposed stiffening, where, depending on the activation of the steel bracing, a reduction in horizontal deformations of the footbridge occurred (in agreement with the numerical solution). Different tensioning of the steel bracing led to asymmetrical behaviour in the longitudinal direction of the footbridge. Given the sensitivity of the structure to this stiffening, it is necessary to ensure the same activation of the stiffening in each module. The magnitude of residual deformations depends on the maximum force achieved with the given stiffening configuration. With active bracing of the footbridge, there was no exceedance of horizontal limit deformations at a force of approximately 6.0 kN in any case.

Tab. 2 Horizontal deformations of the bottom flange.

			Loading 2	**Loading 3**	**Loading 5**	**Unloading 3**	**Unloading 2**	**Unloading 0**
			2.0 kN	*3.0 kN*	*5.0 kN*	*3.0 kN*	*2.0 kN*	*0.0 kN*
Horizontal deformation [mm]	**Variant 1**	**1.2.**	*1.94*	*3.14*	*6.16*	*5.13*	*3.87*	*1.18*
		3.1.	*4.09*	*6.72*	*13.38*	*11.80*	*9.19*	*3.63*
		4.1.	*2.01*	*3.42*	*6.94*	*6.04*	*4.63*	*1.63*
	Variant 2	**1.2.**	*11.62*	*15.56*	*21.06*	*19.08*	*16.92*	*5.15*
		3.1.	*22.56*	*31.98*	*46.89*	*43.48*	*38.76*	*15.97*
		4.1.	*12.57*	*16.84*	*23.28*	*21.04*	*18.68*	*6.37*
	Variant 3	**1.2.**	*15.33*	*24.30*	-	*28.48*	*21.96*	*4.82*
		3.1.	*29.62*	*44.43*	-	*52.83*	*41.09*	*10.39*
		4.1.	*15.44*	*24.38*	-	*28.62*	*22.05*	*4.93*
	Variant 4	**1.2.**	*0.06*	*1.02*	*3.13*	*2.11*	*1.31*	*-0.34*
		3.1.	*3.40*	*5.48*	*9.97*	*7.65*	*5.97*	*2.05*
		4.1.	*1.39*	*2.32*	*4.42*	*3.40*	*2.64*	*0.95*

4 DISCUSSION

The experimentally obtained results clearly indicate that the bracing has a positive effect on the horizontal stiffness of the footbridge, confirming the behaviour of the numerical model. In the upcoming planned load test, it makes sense to focus on the stiffness of the bracing, which will serve as a basis for refining the numerical model.

The experimentally obtained results are compared with the numerical model in Tab. 3. As a result, the numerical model can be refined to include permanent deformations. After refining the model, it will be possible to conduct numerical studies of the modular footbridge without horizontal bracing, with considerations for the need for a full-scale experiment. The comparison in Tab. 3 indicates that during loading, the actual structure was approximately 1.26 times softer than the numerical model. For accurate numerical modelling of this type of footbridge, it will be necessary to define the stiffness in a way that permanent deformations persist even after unloading the structure.

Tab. 3 Comparison of the numerical model and experimentally obtained results of the unstiffening fully composite modular footbridge at mid-span.

		Loading 2	**Loading 3**	**Unloading 3**	**Unloading 2**	**Unloading 0**	**Limit**
		2.0 kN	*3.0 kN*	*3.0 kN*	*2.0 kN*	*0.0 kN*	*L/250*
Hor. def. [mm]	**Num model. Stiffened**	*23.44*	*35.16*	*35.16*	*23.44*	*0.0*	*32.0*
	Experiment Unstiffened	*29.62*	*44.43*	*52.83*	*41.09*	*10.39*	
	Difference	*6.18*	*9.27*	*17.67*	*17.65*	*10.39*	
	Ration	*1.26*	*1.26*	*1.50*	*1.75*		

The comparison of the numerical model and the experiment of the fully composite modular footbridge with stiffening is presented in Tab. 4. In the case of the first reinforcement configuration, the stiffness of the footbridge during loading was approximately 1.5 to 2.05 times lower than determined by the numerical model. This range is based on the dependency of deformation on force, as shown in Fig. 7. For the second configuration, the range was 1.30 to 1.55. This indicates that in the case of Variant 2, the steel cables were more activated before the start of loading. The residual deformation for Variant 1 was 21.23 mm, measured at a force of approximately 6.9 kN. For Variant 2, it was 12.66 mm at the highest load of approximately 6.01 kN. Despite the insufficient activation of the stiffening compared to the numerical model, the limit value of horizontal deformation was not exceeded, and it had a positive effect on the behaviour of the structure.

Tab. 4 Comparison of the numerical model and experimentally obtained results of the stiffening fully composite modular footbridge at the mid-span.

		Loading 2 *2.0 kN*	**Loading 3** *3.0 kN*	**Loading 5** *5.0 kN*	**Unloading 3** *3.0 kN*	**Unloading 2** *2.0 kN*	**Unloading 0** *0.0 kN*	**Limit** *L/250*
Hor. def. [mm]	**Num model. Stiffened**	*2.61*	*3.91*	*6.52*	*3.91*	*2.61*	*0.0*	*32.0*
	Experiment Stiffened 1	*4.09*	*6.72*	*13.38*	*11.80*	*9.19*	*3.63*	
	Experiment Stiffened 2	*3.40*	*5.48*	*9.97*	*7.65*	*5.97*	*2.05*	
	Ratio 1	*1.56*	*1.72*	*2.05*	*3.02*	*3.80*		
	Ratio 2	*1.30*	*1.40*	*1.53*	*1.95*	*2.28*		

5 CONCLUSION

In the design of footbridge structures, it is essential to consider the loads acting both vertically and horizontally on the footbridge. In the case of the introduced fully composite modular footbridge, previous research activities revealed low stiffness in the horizontal plane. For a practical application of the structure, it was necessary to increase the horizontal bracing of the structure in the plane of the crossbeams using steel cables that do not disrupt the modular system. This article examines the impact of steel cables on the horizontal stiffness of the fully composite footbridge determined through a load test.

- Footbridge behaviour relies on construction precision, particularly joint connections.
- The footbridge without horizontal bracing exhibits significantly lower stiffness compared to when steel ties are used.
- The level of stiffening depends on the magnitude of prestressing/activation of the steel bracing.
- Stiffening follows a modular system and utilizes easily accessible components.

The obtained results provided crucial insights for the development of the fully composite modular footbridge for its intended practical application. In the next phase of the research, there are plans to determine the stiffness of the bracing using an additional planned load test. The results will be utilized to optimize the numerical model and serve as a basis for conducting dynamic analysis, which is an integral part of the footbridge design process.

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