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HIGH SPEED RAIL – THE CURRENT CHALLENGE TO POLISH RAIL TRANSPORT

Sławomir Karaś

Lublin University of Technology
Department of Civil Engineering and Architecture
Nadbystrzycka Street 40, 20-618 Lublin, Poland
tel.: +48 81 5384383, fax: +48 81 538-41-77
e-mail: s.karas@pollub.pl

Andrzej Krasnowski

Railway Design Office
Movares Lublin
Okopowa Street 5, 20-022 Lublin, Poland
tel.: +48 81 5326968, fax: +48 81 5322141
e-mail: andrzej.krasnowski@movares.pl

Abstract

The increase of the role of rail transport in comparison with road and air ones was an important task for transport engineering in western Europe and Japan in the 1970s. Now the problem is not completely closed but the majority of the establishments formed in the beginning were successively solved. The main assumptions could be grouped into environmental protection and sustainability, decreasing the travel time connected with accessibility, safety, comfort for passengers, considering freight transport, as well.

The high speed of the moving train was the main criteria of any engineer approach i.e. from the point of view of energy safety, limiting pollution, ability to transport thousands of people and tons of cargo. High Speed Rail – (HSR) means the speed between 250 to 400 km/h. This divides tracks into two groups: ordinary tracks and special ones, which results in two possible ways: adopting existing tracks or building new railways.

Recently the program of HSR has been decided to put in motion in Poland. The situation here was very complicated. Many abandons such as complete lack of road highways, backwardness in air transport as well as rail transport, which means abandons in track conditions and rolling stock. At least, actually no existing haulage transport. In those circumstances, any rational first step was to be taken i.e. a technical diagnosis and an estimation of the existing railway system including culverts and bridges as important elements of trucks.

The paper presented here contains a short survey of statical and dynamical field test results and FEM analyses as an extension to the train speeds 1.2·350 = 420 km/h.

Keywords: *rail transport, high-speed rail, bridges, HSR, dynamics*

1. Theoretical background

In Poland, many years earlier, the problem of the moving load on a bridge was investigated by many researchers. The first work was done by Piszczek [20] (1958), where the loss of plate stability was researched. In his monograph work on metallic bridges, Szelągowski [25] searched for critical velocity by means of second type Lagrange equations. However, the obtained result led to seeming solutions when the de l'Hospital rule was used.

Without any exaggeration, we can say that the explosion in the field of dynamical problems considering moving statical force and mass' forces was connected with two *schools* led by prof. Wacław Szcześniak and prof. Jan Langer and Marian Klasztorny.

In the 1970s, Langer published a series of works [13, 15, 16] on moving loads on bridges.

Klasztorny in his doctoral thesis [9] solved the problem of moving forces being in contact with the palate through rheological dampers. His further works [11, 12] explored many variants of that problem including rail traffic. The last work [18], which was a monographic one, on HSR bridges founded the basis for caring out dynamical bridge testing and analyzing.

The second school was due to Szcześniak and his fellow-workers' activity. Among many published papers [22, 23] are necessary to recall here, where the inertial (mass) action onto beam or plate structures was investigated. In [23] the rheological rail embankment was analyzed from the point of view of its stability and critical velocity under the moving train. Szcześniak emphasized the Ukrainian works and contribution in dynamics, he especially underlined the significance of Jakushev's approach to the understanding of moving mass forces. This caused the fundamental discussion between Szcześniak and Langer together with Klasztorny, which had a form of article [14] for which Szcześniak was appointed a peer reviewer.

The comprehensive bibliography on dynamical problems with moving loads can be found in [23]. At the end of this short survey of the Polish papers let us recall the chapter title – an exert from [10]: *Experimental testing – the basis of rail bridge dynamics development.*

In short, we can summarize the dynamical problem of moving loads on the bridge:

– the description of dynamics,
– dynamical (rheological) characteristics of material of the structure (ground, beam, plate),
– reciprocal interaction between structure and loads action.

The basic relation defining dynamics comes from the equilibrium condition, which could be of elastic, viso-elastic or elastic-plastic problems and has the short form as beneath

$$\nabla_m \sigma^{mn} + \rho f^n = \rho \partial^2_{(t)} u^n . \tag{1}$$

This relation obeys also quasi-statics and statics. The terms used above are commonly known and as it is, will not been commented. The second basic formula is a decomposition of any function into Fourier series

$$F(\xi,\tau) = \sum_j^{\infty} F_j(\tau) f_j(\xi) . \tag{2}$$

where $F(\xi,\tau)$ is an analyzed function, F_j are its Fourier's coefficients and $f_j(\xi,\tau)$ are set up orthonormal basic functions. By means of (1), (2) and fulfilling boundary and initial conditions the majority of dynamical bridge problems can be solved. Those formulae, in many admissible variants, were used as computational procedures, thus we can get an elementary dynamical characteristic i.e. natural frequencies and theirs forms, Fig. 1 and 2.

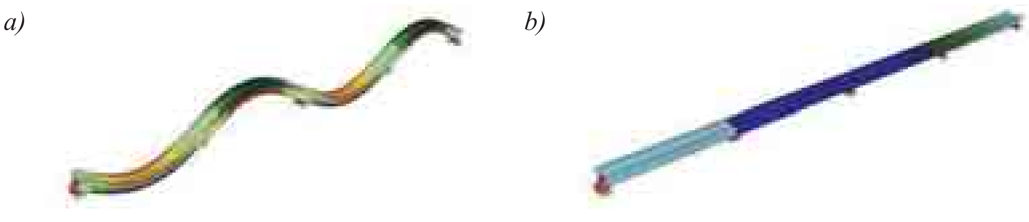

Fig. 1. The 1st frequency 3.615 Hz (a) and the 5th frequency 7.470 Hz (b) and theirs forms

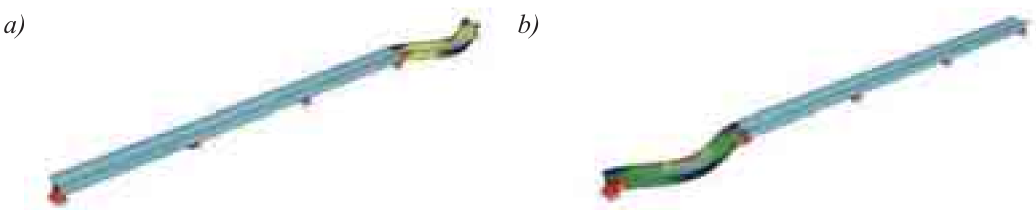

Fig. 2. The 6th frequency 11.740 Hz (a) and the 7th frequency 11.740 Hz (b) and theirs forms

The estimating of dynamical response of different type of investigated bridge structures was the aim of Paultre, et. al. paper [19]. There, the authors discussed results received after over 30 year testing in Canada, USA and Europe. The dynamic factor in case of deflections or strains was assumed a fundamental characteristic.

The work finalizing European Integrated Research Project *Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives* [3], which summarized efforts in different European countries related to the idea of the sustain ability of rail bridges has the special position. The comprehensive list of sustain problems was treated in detail, starting from old to just new bridges, always focusing on dynamics. There some useful diagnostic procedures of existing bridges were formulated, usefully supported by included examples.

2. Practice in Poland

The work of Niemierko [18] was the first complete approach to the dynamics of rail bridges. He tested and concluded on truss (Warren) and arc (Langer) structures on the basis of obtained results including deflection, strain, imperfections and acceleration distributions during the train moving.

It would be enough if one focuses on the conference *Contemporary methods of bridge strengthen and reconstruction,* which is held near Poznan [1, 17, 18, 21] each year. In [8] there was the method of diagnosis and interpretation of structure response formulated, which focused on the relation between the train speed and acceleration on the bridge. This acceleration value was crucial because of truck stability. In other papers the authors report on the results obtained during dynamical testing of various types of bridges on *E-65* main line (*CMK* – in Polish). Many useful conclusions created a pattern to further investigations. Let us now discuss an interesting dynamical event which was shown in [2], Fig. 3.

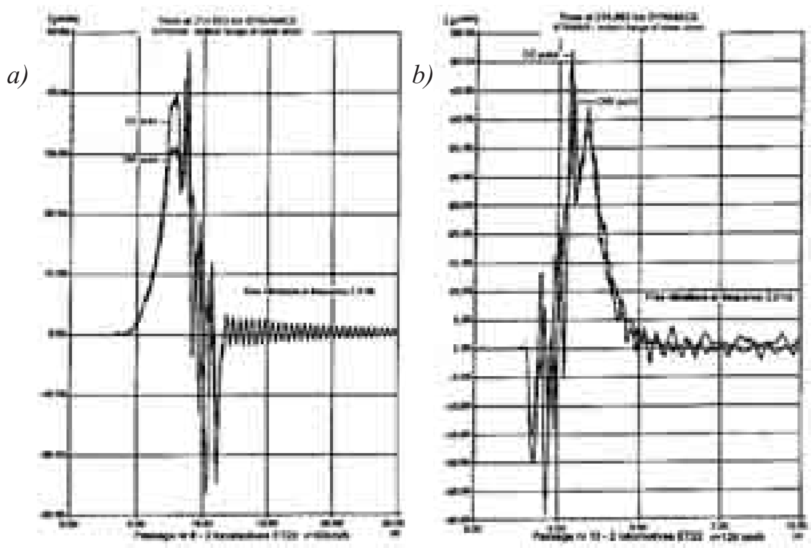

Fig. 3. The distribution of strains at a bottom flange of Warren's truss at velocities appropriately a) 60 km/h, b) 128 km/h; (by a courtesy of the [25] authors: Apanas L., Sturzbecher K.)

Let us forget for a moment about those initial and residual damping parts of graphs and notice the mirror reflection. This accidental and rare situation shows a variety of possible dynamic responses. Here we have an exchange made in the time of the same strain waves, which are lower at 60 km/h and quicker when the speed was 128 km/h. On the other hand, this could be typical in dynamics. Both explanations show that the analyst has to read graphs very carefully, paying attention to dynamical rules. Certainly, of course, the right part of the graph in Fig. 3b is not a regular damping, is no harmonic.

In [26] one can read about the first reconstruction of the existing rail bridge over the Pilica River, which was adopted, to the needs of high speed. It is important to stress here that the design was connected with constructional works. The advanced computational modelling led to the good convergence between designed values and measured during the proof tests at a ~20% level, which is not bad for a new structure and in case of adoption is rationally perfect.

3. The report on own works

The bridges located on the E-65 main line at the Grodzisk Mazowiecki – Zawiercie sector were investigated in accordance with adoption to high-speed train operating. The range of expert works involved:
– 2 steel rail Warren trusses of spans 51.0 and 93.0 m,
– 1 Langer arc of a span 75.0 m,
– 1 steel plate girder bridge with the RC deck located near to the neutral axes of the structure,
– 19 composite of the steel-concrete type objects, 14 of them have simple forms and others were continuous, and among them 1 of two-spans, and also 1 as four-spans,
– 7 RC bridges made with use of precast units,
– 2 RC monolithic, 1st of frame structure and 2nd with plate deck,
– 68 RC culverts, among them 59 made of precast frame unit, light: 1.0×1.0 m 1.5×1.5 m, 2.0×2.0 m, in different variants: one, two and three tubes; the others 9 monolithic vault at dimensions 3.0×2.49 m and in variants as above.

All of those constructions were erected in the 1970s.

The estimation was carried out by two expert groups:
– Construction Diagnostics and Repair – Tomasz Kordiak (Diagnostyka i Naprawy Konstrukcji – Tomasz Kordiak), and
– Bureau of Railway Design Movares Poland, the branch in Lublin (Biuro Projektów Kolejowych (BPK) Movares Polska Oddział Regionalny w Lublinie).

4. Culverts

At the very beginning did the problem of culvert definition [27] rise. Culverts could be treated in different manners in road, rail, bridge and water engineering. Finally, an indirectly introduced definition at EC 1991-2 [4] was assumed, which was then mixed with the classical definition that a culvert is a relatively small pass located in the road or rail embankment. The new criteria defining the dynamical effect and its reduction [7] were different from those used during the design process in the 70s. The following analysis shows the safety reserve of 8 to 20 % for ULS, Fig. 4.

a) b)

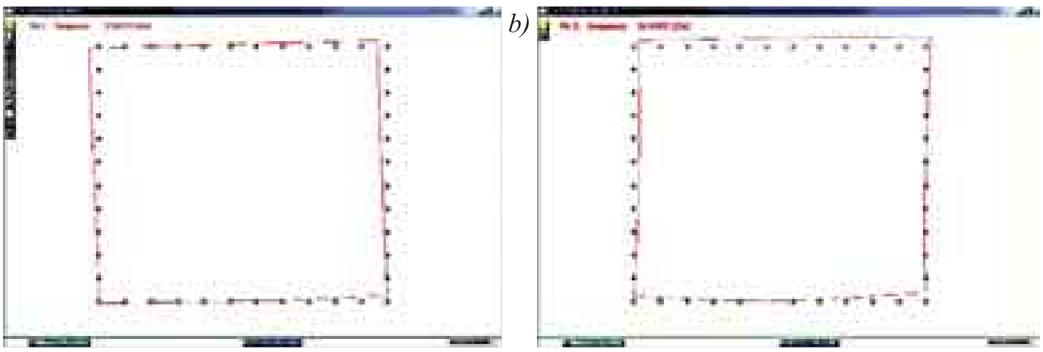

Fig. 4. Box culvert, the first two frequencies appropriately equal at 23.85 Hz (a) and 24.84 Hz (b) and theirs modes

To reduce the *jump and strike* effect, the solution shown in the Fig. 5. was proposed There the *jet grouting* technology should be used vertically and horizontally as well.

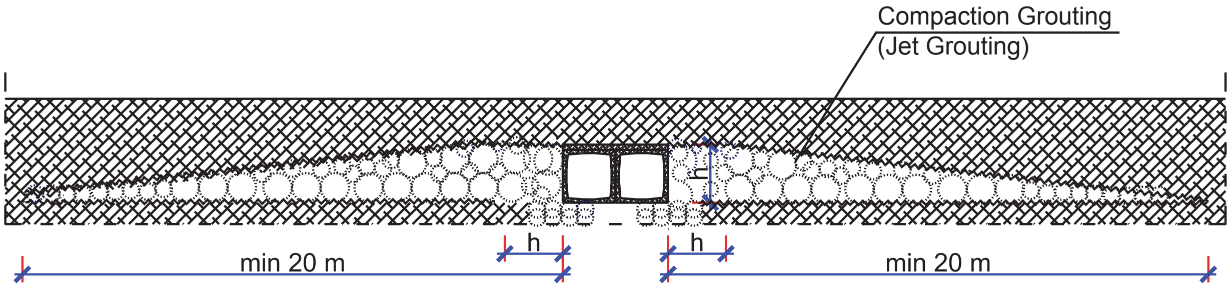

Fig. 5. The proposal scheme of ground stabilizing in the neighbourhood of the culvert

5. Abutments – supports

Abutments were made as RC. Their conditions in the sense of ULS are qualitatively not bad but service condition is adjacent to pure. After over 40 years of working, exposed to no-leak tightness of expansive-joints, surface and deep corrosion joined with probably insufficient freeze resistant of concrete produced in the 70s – all these are effective in the emergency of their reconstruction, Fig. 7.

Fig. 7. Lateral surfaces of investigated abutments

6. Composite of steel-concrete bridge decks

In the beginning let us say that in case of the dynamic analysis there were two methods used, available and admissible in accordance to EC 1991-2:

– loads were defined as HSLM trains with an increasing speed and
– the method, where for the first one, the most aggressive Universal Train like one from the HSLM sets is searched; universal in the sense of critical wavelength of excitation; such a gotten train was used as a selected one for further loading.

The investigations were carried out in two parallel ways:

– experimental testing of real structure when the train speed was about 160 km/h and
– analytically by means of computational FEM programs, which is an extrapolation to higher speeds, up to 420 km/h.

The statical approach was defined as LM71 of a class $\alpha = 1.21$ with dynamic factor $\Phi_{2,3}$.

Beneath, in the graphs, one can see an integrated output of all elements of the diagnosing carried out. In Fig. 8, the convergence to the results of the tests is visible as well as to statics. Not so clear are the results of the distribution of accelerations and deflections being in the function of increasing velocity. In Fig 8a, the local tendency to the instability is visible. However, not strong enough to be actually dangerous. Opposite, in Fig. 8b one can read an irregularity point for the velocity value ~340 km/h, which was real instability for deflection and acceleration as well. For both graphs, it was characteristic that the limit value of acceleration equal to 3.5 m/s^2 is accessed for the speed ~250 km/h.

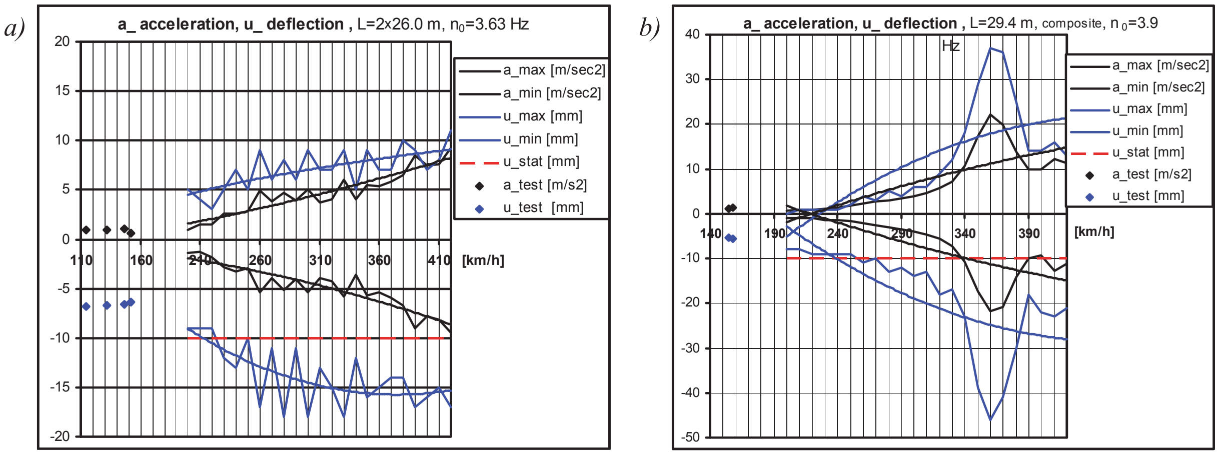

Fig. 8. Results for continuous 2 span bridge of 2x26 m (a) and one span simple structure of the span 29.4 m (b), for both the value of first frequency have the same range

Even when two bridges look very similar in shape and have the same length and additionally the test results for a speed of 160 km/h are almost the same, they can appear completely different when the dynamics due to high speeds was considered. This was shown in Fig. 9. The run of obtained curves in both examples have an exponential form, which was in contrast to Fig. 8 where curves were parabolic.

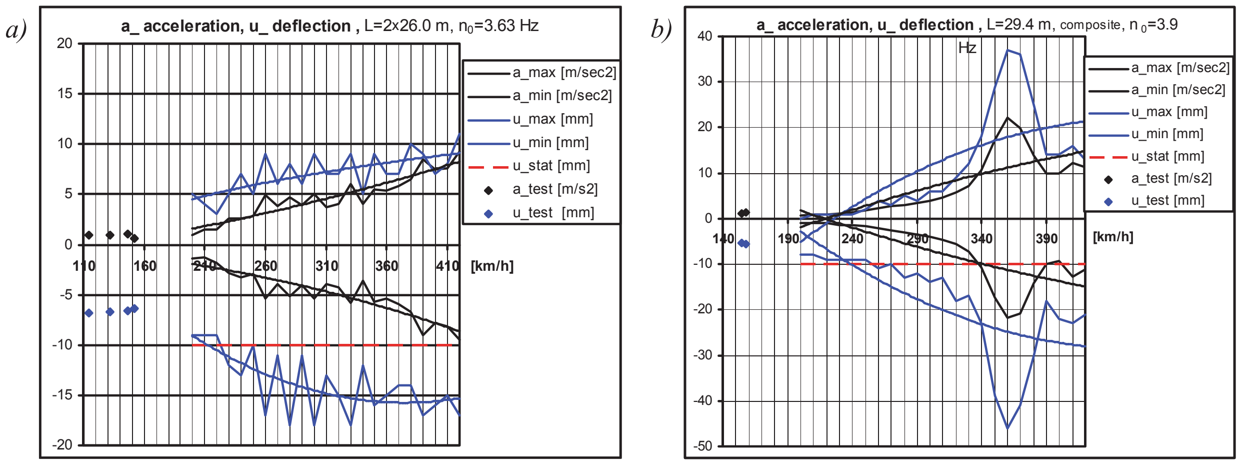

Fig. 9. Results for two bridges of the same type and span lengths, but having different values of first frequencies

Those results bring us to the conclusion that in a dynamical sense the bridge presented in Fig. 9a was stiffer than this in Fig. 9b. According to EC 1991-2, there we found

$$n_0 = \left\{ \begin{array}{l} 94.76 \cdot L^{-0.748} = 94.76 \cdot 17.4^{-0.748} = 11.19 \\ 80 / L = 80 / 17.4 = 4.59 \end{array} \right\} \text{Hz}, \tag{3}$$

which further enlarges existing inconsistency.

It is possible for the train speed up to 250 km/h by reconstructing the existing objects. For a further velocity increase, it is proper to build new structures. The basic criteria for dynamic stiffness measure are the value of first frequency.

7. RC bridges

After diagnosing concrete bridges was possible to note similarities with [6, 17] conclusions. Those structures were dynamically stiff and their basic frequency value was 2 or 3 times higher then for composite ones.

8. Long bridges

For Warren trusses of the 93.0 m and 51.0 m spans the results are shown in Fig. 10. It was noticed that the influence of rail track eccentricity had no essential influence upon FEM results.

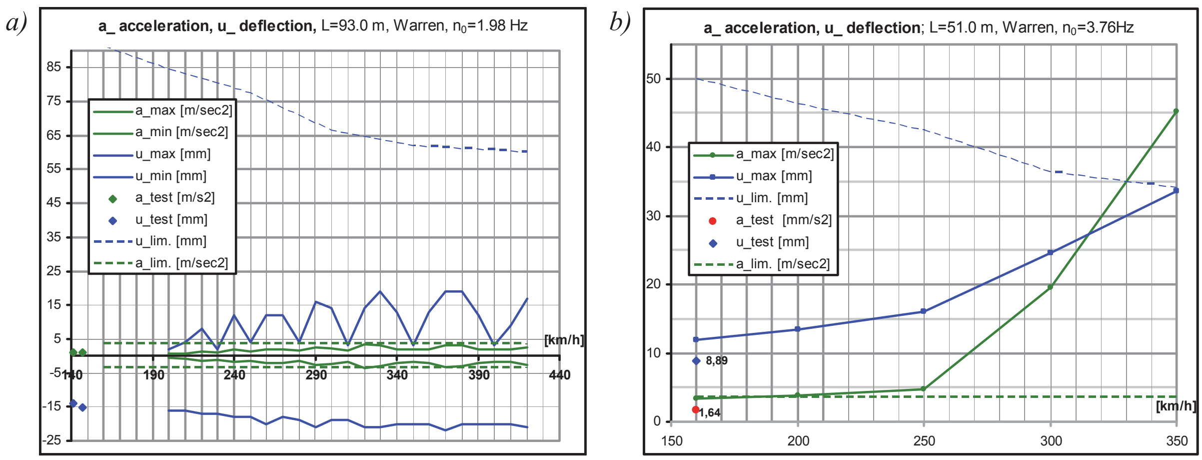

Fig. 10. Warren truss bridges of different span

The individual approach was necessary, which is illustrated by above graphs. If we still estimate the dynamic stiffness by the value of first frequency the shorter bridge should be treated as stiffer – and this is not true. Although the deflection meets its limit value only just at the velocity of 350 km/h. The acceleration crossed the limit of 3.5 m/s^2 just at the beginning.

In case of Warren L = 93.0 m the structure safety was guaranteed from the beginning to the end of the scope.

The Langer arc has the span of L = 75.0 m. It is commonly known that such an arc has a *week point* at about L/4 distance from the beginning of the span. Due to this, the field tests were focused on this point as well as on the mid point. Beneath are shown diagnosing results in Fig 11a, assisted by the graph taken from the work [18], Fig 11b.

It is visible that the results are supplementary. The accelerations in Fig. 11a are insufficiently large in comparison with the admissible value of 3.5 m/s^2, on the other hand, the deflection is saved with the margin of ~50%. From the dynamical point of view, we have two hazardous moments i.e. at a velocity value of 280 km/h and of 420 km/h. Both acceleration and deflection graphs point out the tendency of singularities.

9. Conclusions

The above report contains a list of difficulties in interpreting obtained experimental and numerical results. On that basis, it seems to be true that in case of dynamics the individual approach is necessary. The simple analysis containing only vertical displacements and accelerations is not sufficient. The lateral effect i.e. lateral bridge stiffness or rather its lags was in the majority of cases the reason for acceleration overflow. The second scarcity is forking between the test ability where the maximum velocity was about 200 km/h and standard needs where train velocities are ~350 km/h. Although the used FEM procedures were proved, the designer has a field for hesitation and uncertainness.

The classical concept of construction stiffness is strictly connected with statics. In dynamics the first frequency value plays a similar role, but *first frequency* should been understood as a bending one. Considering bending waves, it means vertical and normal to the longitudinal axis of the structure, and not only normal to the axis of a structure element. For other forms, i.e. lateral bending, torsion, shearing, and elongation the frequency values should be grater then the first one. Under such conditions, the first frequency value plays the role of a stiffness measure, and the best one would be when greater or equal to 9 Hz.

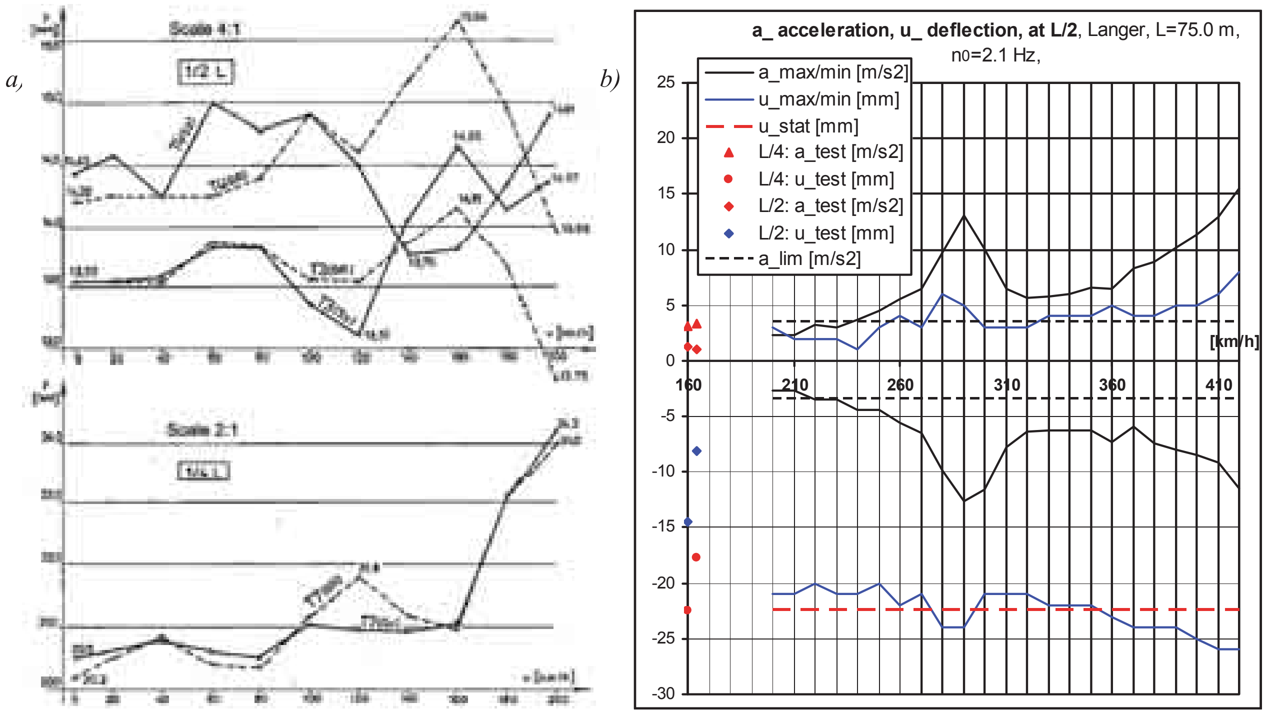

Fig. 11. (by the courtesy and acceptance of the [19] author – Niemierko A.) - Results of dynamic diagnosing of Langer arcs, both of the span L=75.0 m

Probably such defined conditions also fulfil needs according to acceleration values, which are differentially connected with displacements.

Heavy structures are more proper for getting better dynamical characteristics. This was visible here when RC bridges would be matched with composite or steel ones. Owing to this comes a suggestion for rebuilding – to use a rather weaker steel class, S235 for example, instead of higher classes.

Probably a culvert is a simple structure, simpler than a bridge, but it was not a sufficient motive to omit this structure type in standards. It will be very useful to know how to treat the dynamical problem of the integrated soil-shell culvert using simple EC procedures.

The integrated structure – this could be the answer to many questions related to dynamical difficulties. In Fig. 12 there is a proposal of abutments rebuilding shown. Instead of duplicating existing abutments, it is possible to integrate an existing abutment together with simply supported decks and now create a frame.

The list of advantages contains as follows:
- stiffer carrying deck in a statical and dynamical sense,
- absence of bearings and expansive joints,
- simple and not expensive composite bridge technology,

– the new role of abutment wings which create approaches to the abutment zones.

It seems that building the HSR system in Poland would be more complicated and extended, in technical sense, than building highways, as it was mentioned in the title of the paper. Due to this, it is a great challenge for today and future engineers' generations.

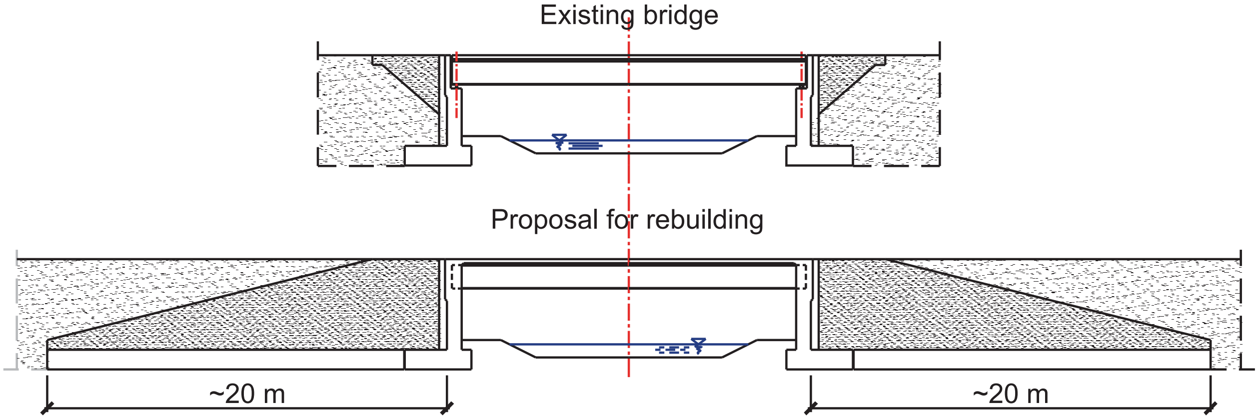

Fig. 12. Rebuilding by change of statical scheme

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