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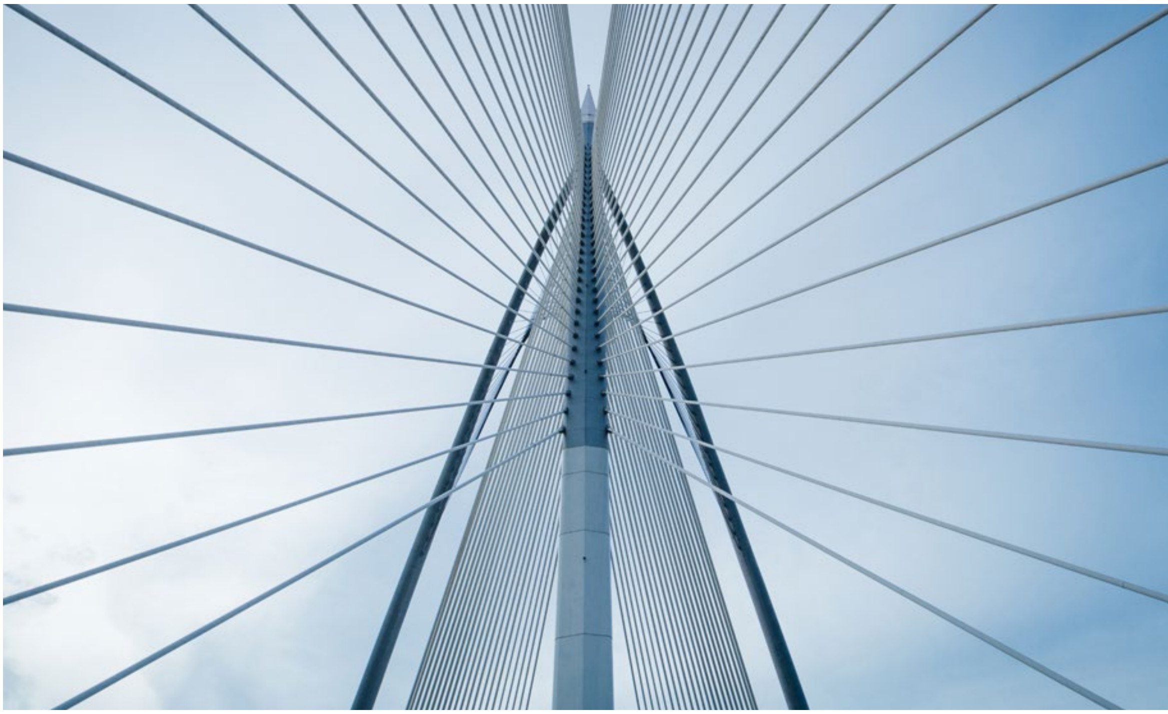


Validation on bridge superstructures

Modal-based monitoring system

Application notes

Motivation and goal

More and more, the increasing stress on infrastructures provides the challenge of investigating and evaluating the existing structures with regard to safety and the resulting remaining useful life. Reliable, technically feasible and economical solutions for metrological monitoring are necessary in order to guarantee structural safety and fitness for purpose. This is the key prerequisite for obtaining meaningful information about damage processes and the current structural properties.

A metrological solution model for a modal-based monitoring system for bridge superstructures is being developed at the Reinforced Concrete Department of the Institute for Reinforced Concrete and Building Materials at KIT (Karlsruhe Institute of Technology) as part of the ZIM cooperation project "Development of a system for the modal-based damage analysis and monitoring of bridge superstructures."

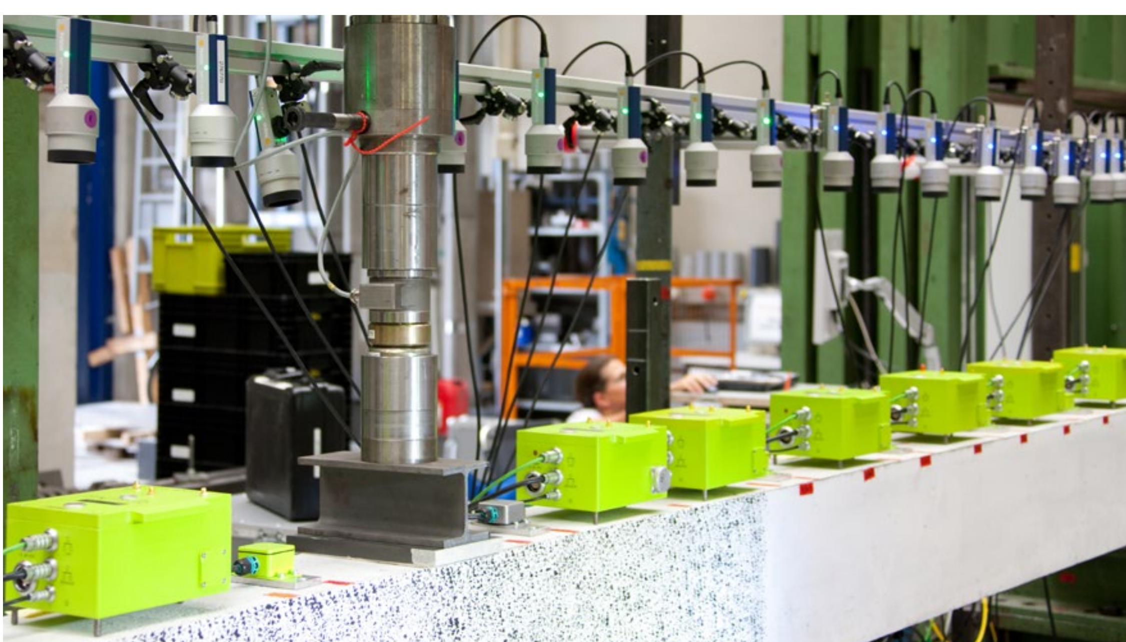
Like all structures, bridges exhibit vibration characteristics when excited, which can be described by modal parameters such as eigenfrequencies and eigenmodes. The basic consideration for a modal-based monitoring system is that damage processes are accompanied by stiffness changes in the structure, which in turn lead to measurable changes in the modal parameters. The modal parameters, eigenfrequencies and eigenmodes can be measured and characterized in order to obtain in-depth information about the bridge condition, its load-bearing capacity and the remaining service life.

Setup

Component tests were carried out at the Materials Research and Testing Institute in Karlsruhe under the direction of Ms. Mareike Kohm for the experimental verification and testing of a modal-based monitoring system. A 6.5 m long simple reinforced concrete beam served as an analogous model for the bridge. The reinforced concrete beam was intact at the beginning of the experiment and was progressively damaged during the course of the investigations by a path-controlled hydraulic cylinder; see Figure 1. Incremental crack formation occurred as a result of the centric bending tensile stress on the reinforced concrete beam. This was documented for subsequent evaluation both manually and with the GOM Aramis optical measurement system.

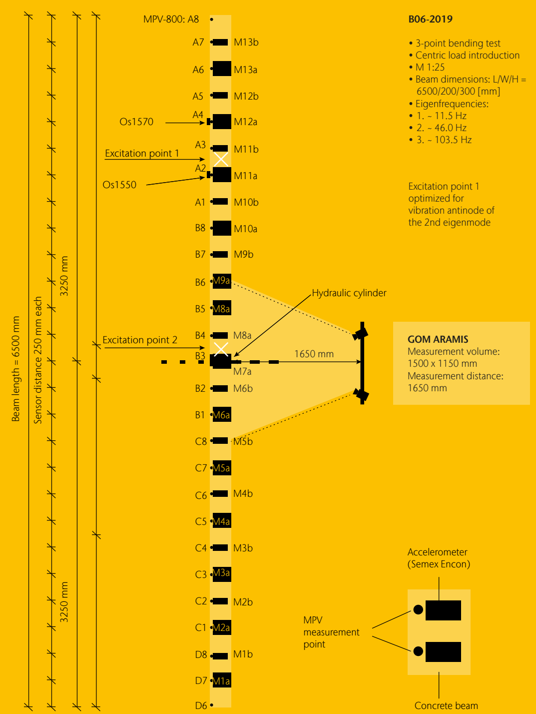
Acceleration time histories were recorded at 25 measuring points using MEMS-based accelerometers from Semex-Engcon for the metrological testing and verification of the modal parameters. The Polytec Multipoint Vibrometer (MPV-800 system) with 27 sensor heads on 4 optical units was used for the same 25 measuring points and 2 additional measuring points on the support axes in order to check and verify the metrological results of the accelerometers. The MPV measures vibrations on a non-contact basis and is based on the laser Doppler vibrometry principle. Each optical unit of the MPV con tains eight sensor heads that can acquire measurement data simultaneously. The MPV is therefore particularly suitable for non-repeatable events such as damage. Two Fabry-Perot fiber sensors (OS) from Luna Technologies (distributed by Polytec) were also used as accelerometers for additional verification of the measurement data.

The beam was excited at two positions by means of a simple manual rubber hammer. The modal parameters were then determined using the Frequency Domain Decomposition Method. This method is one of the processes used in Operational Modal Analysis, where the modal parameters are estimated solely on the basis of the response vibrations of the structure. The excitation forces therefore do not have to be measured. When transferred to real bridge structures, this means that natural non-measurable excitation sources such as traffic, wind and microquakes can be used, with the result that there is no traffic disruption during the monitoring measure. The positioning of the sensors on the reinforced concrete beam can be seen in Figure 1 and Figure 2.

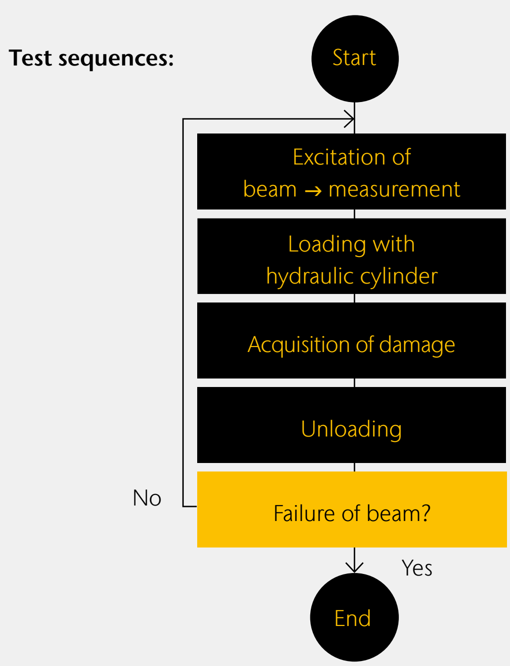


1
Loading with the hydraulic cylinder (middle), MPV laser sensor heads (top) and MEMS sensors (green objects on the reinforced concrete beam)

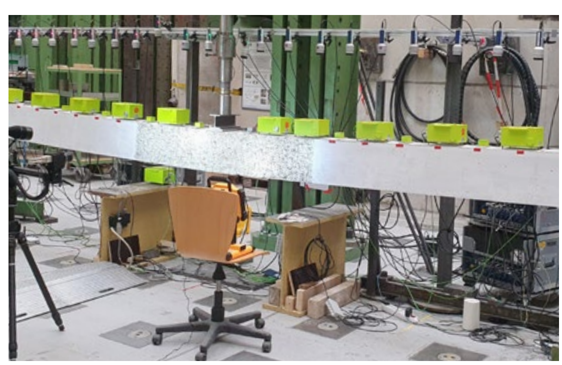
2
Scheme of the measurement setup



3
Test setup: MPV laser sensor heads (mounted above on the Bosch stand) and MEMS sensors (green objects on the reinforced concrete beam)

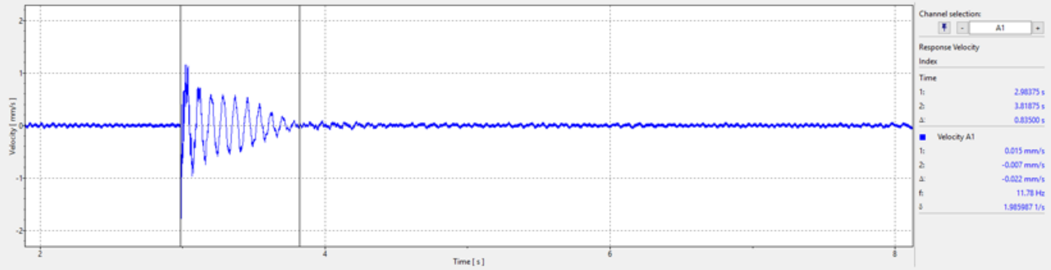


4
Excitation with the rubber hammer at excitation position 1 (maximum of the vibration antinode of the 1st eigenmode)

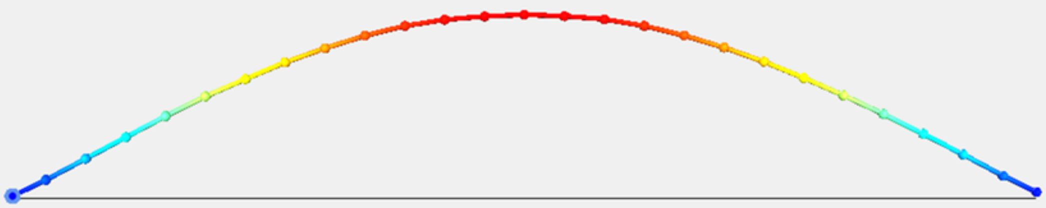


5
Loading of the reinforced concrete beam

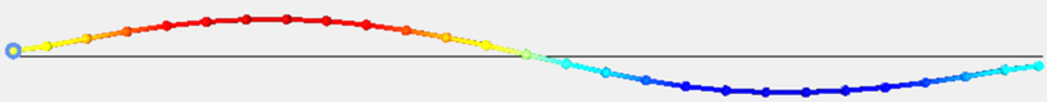
The 27 MPV sensor heads were aligned with the top of the reinforced concrete beam (see Figure 3) and attached to several assembled Bosch profiles. All 27 measuring heads of the four optical units were operated in 1D mode. The OS measuring systems were attached to two lateral measuring points at the height of the MEMS sensors. All measuring points had to be acquired synchronously for each system for the comparison and verification of the MEMS with the MPV system. The MPV-800, which can acquire up to 48 channels simultaneously thanks to the synchronous measurement data acquisition, was developed precisely for this task.



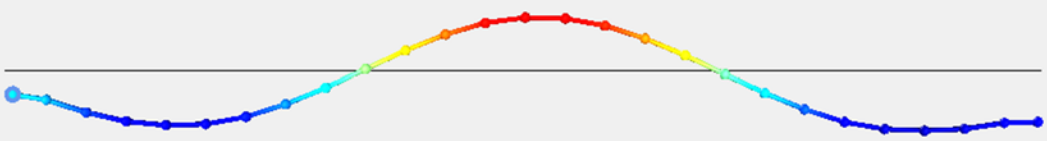
6
BE00 Pos1 vibrational velocity measurement in the time domain



7
BE00 Pos1 10 Hz 1st Eigen mode



8
BE00 Pos1 40 Hz 2nd Eigen mode



9
BE00 Pos1 92 Hz 3rd Eigen mode

Test procedure

Ten measurements per position were recorded at a defined trigger threshold by means of the three measuring systems MPV, MEMS and OS. The sample time was 15s in order to acquire the decay of the vibration in the time domain. The first series of measurements per excitation point (Pos. 1 and Pos. 2) was taken before the initial loading with the hydraulic cylinder.

This measurement was regarded as an undamaged reference state and is referred to as BE00 in the following. The reinforced concrete beam was loaded and unloaded by means of a hydraulic cylinder located in the middle of the test beam after each complete series of measurements at both excitation positions. The excitation of the test beam with the rubber hammer was always provided in the unloaded state. 16 stress levels were recorded until the reinforced concrete beam failed.

Evaluation

The assessment using the MPV Multipoint Vibrometer enabled a clear visualization right from the start (BE00: measurement in undamaged condition) of measurement data in both the time and the frequency domain including resonance frequencies and corresponding deflection shapes in the MPV software.

With the other two sensor systems a graphical display of the response spectra and Eigen modes were not possible on site. These had to be evaluated in a post-processing.

Figure 6 shows the time measurement for BE00. Figure 7, 8 and 9 show the first to third Eigenmode of for BE00 (1st Eigen frequency 11 Hz, 2nd Eigen frequency 45 Hz, 3rd Eigen frequency 92 Hz).

Comparison of the eigenfrequencies between MPV and MEMS with Frequency Domain Decomposition (FDD) method:

The acceleration time histories (determined with the MEMS sensors) were used here, and the velocity time histories (determined with the MPV-800) were applied for validation. Acquisition of the eigenmodes was not possible with only two OS point sensors. The three sensor systems were compared in the next step by means of the natural eigenfrequencies determined via FFT.

The measurement data of the respective measurements within a series of measurements were first compared for each stress level and excitation position and then averaged in order to compare the two sensor systems. The curves of the eigenmodes could be determined from the eigenmodes determined with the MEMS sensors. As a result, the incremental crack formation of the reinforced concrete beam could be detected and localized. The damage process caused by the hydraulic cylinder (incremental crack formation) could be detected from the opening of the first crack by means of the modal parameters.

The progression of the eigenfrequencies over the respective stress levels (BE) is shown in Figure 10, Figure 11 and Figure 12. The blue curves show the eigenfrequencies that were determined with the MPV system; the red ones were determined with the MEMS sensors. The comparison of the eigenfrequencies between MPV and MEMS sensors shows a congruent progression over the stress levels, especially for the second and third eigenfrequency. Apart from its easy handling advantages, the non-contact measuring method is therefore just as suitable for metrology as conventional sensor technology. The scattering in the first eigenfrequency (Figure 10) can be attributed to the material-related non-linearities of the reinforced concrete. Since the vibration amplitudes of the first eigenmode are the largest, the influence of the deformation-dependent non-linear behavior of the concrete is greatest here.

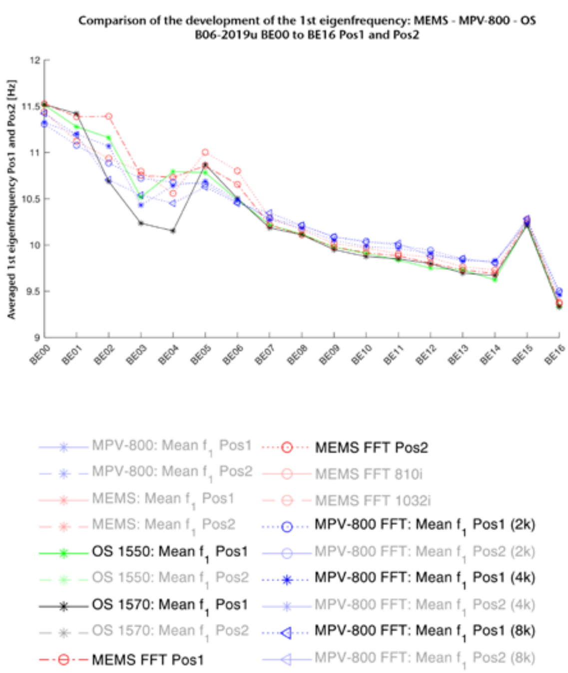
However, the MPV shows an almost congruent progression in the first stress levels between Position 1 and Position 2, while the differences of the MEMS sensors vary somewhat more in this area. Since the influence of the non-linearities is greatest at low level of damage, the scattering decreases as the load increases. For example, the scattering of the first eigenfrequency is only noticeable up to the 6th stress level, after that the scattering is only very small. Both sensor systems also show a significant rise in the first eigenfrequency as the reinforcement begins to yield at stress level BE15. However, a plateau can also be seen in the progression of the MPV and MEMS sensors that was not expected for the first eigenfrequency. In fact, a continuous frequency decrease was expected as in the case of the second and third eigenfrequency.

Comparison of the eigenfrequencies between MPV, MEMS and OS with the FFT method:

Another type of data evaluation method was also used in order to compare the two OS sensors: The modal parameters could not be estimated using the Frequency Domain Decomposition Method owing to the small number of OS sensors. The eigenfrequencies were therefore determined by means of the FFT. The results for the frequency of the first eigenmode are shown below. These results were evaluated by means of a simple FFT.

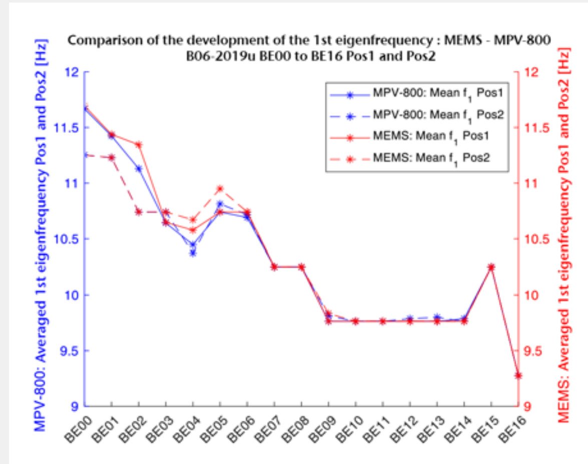
In contrast to the Frequency Domain Decomposition evaluation of the MPV and the MEMS sensors, an FFT evaluation of the first eigenfrequency does not show a plateau for stress levels 9-14, but a slight decay. The causes are still unclear. This behavior occurs with all sensor types, i.e. it does not depend on the sensor technology but rather on the analysis of the data. However, the results of the second and third eigenfrequency of the respective sensor system are virtually congruent, irrespective of the calculation method.

All three sensor systems show a very similar progression with this type of analysis.

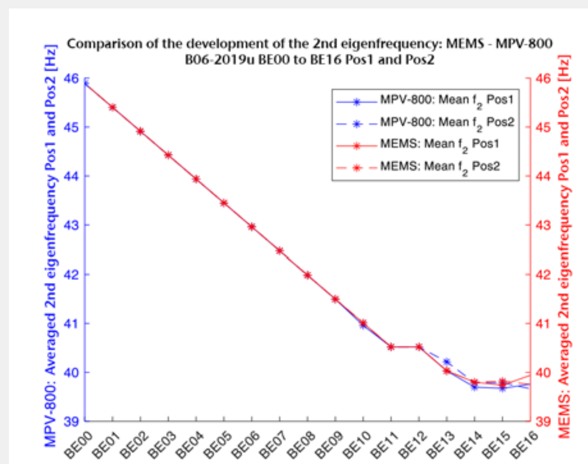


Overall conclusion

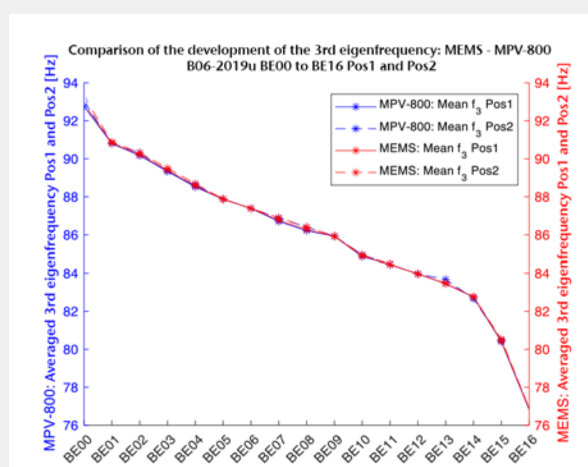
By and large, no significant differences between the three sensor types can be found. As a verification instrument, the MPV-800 Multipoint Vibrometer could therefore confirm the results of the MEMS sensors (monitoring system). The MPV therefore offers an option for the same measurement accuracy as contact sensors. It is also non-contact and flexible.



10 *Comparison of the 1st eigenfrequency*



11 *Comparison of the 2nd eigenfrequency*



12 *Comparison of the 3rd eigenfrequency*

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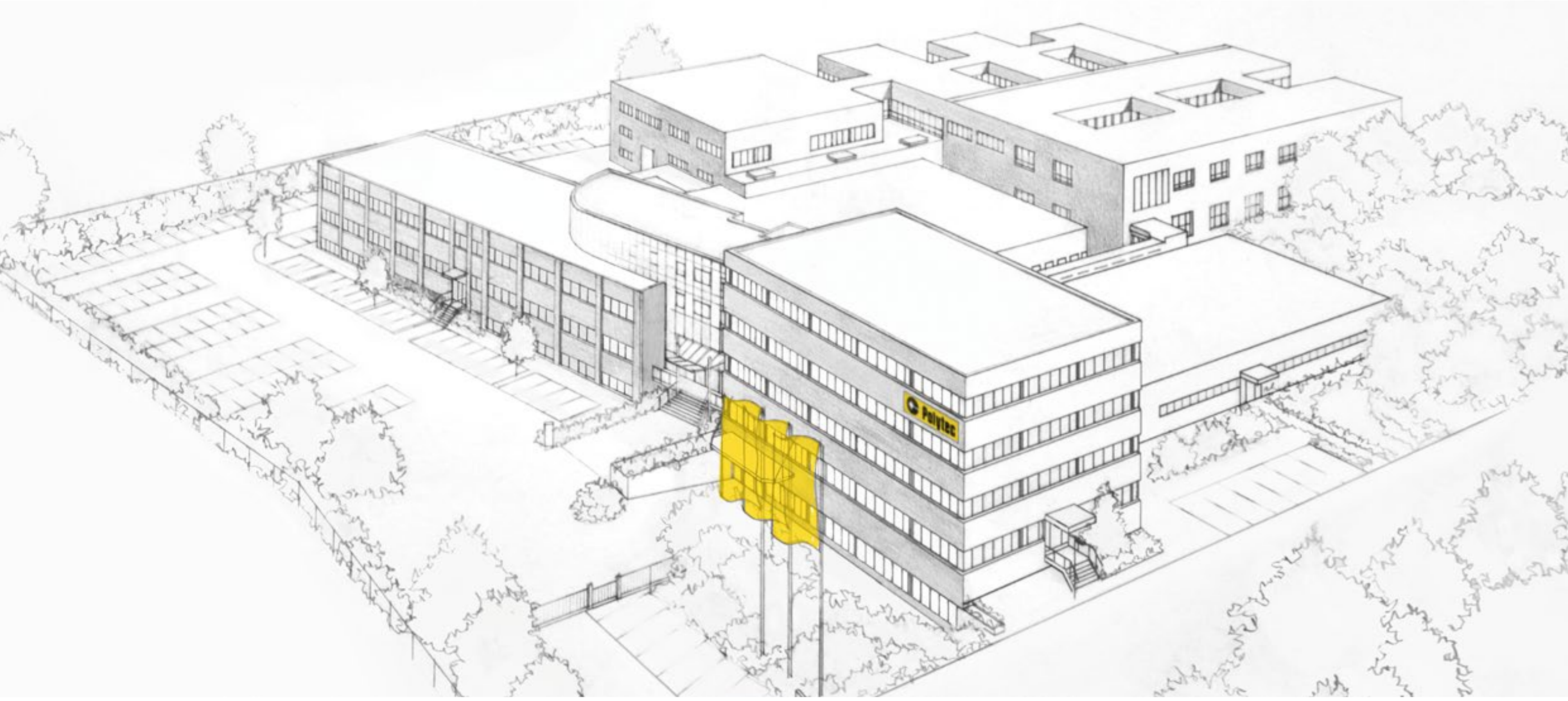

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