Head Office
P.O.Box 440145, D-80750 München
Frankfurter Ring 193, D-80807 München
phone ++49 – 89 / 3 23 94-0
fax ++49 – 89 / 3 23 94-329

Branch Office
P.O.Box 6340, D-44520 Lünen
Zum Holzplatz 2, D-44536 Lünen
phone ++49 – 231 / 4 34 01-0
fax ++49 – 231 / 4 34 01-11

Subsidiary
P.O.Box 55, D-02992 Bernsdorf
Kamenzer Str. 4 - 6, D-02994 Bernsdorf
phone ++49 – 35723 / 237-0
fax ++49 – 35723 / 237-20

Nr. 21gb
VBL / VBA
11 / 2000
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The Control Mechanism of Modular Joints

Watertight modular joints consist of several steel beams that are arranged parallel along the axis of the joint and sealing elements that are located in between these steel sections to seal the individual gaps from protruding water and dirt. Control elements have to take care that the individual gap openings receive their equal share of movement of the total movement of a joint. Another function of the control elements is to transfer the horizontal forces that occur, for example, due to braking forces of a wheel, safely into the edges of the joint.

Of the many proprietary brands of modular joints that are on the market, their fundamental difference lies mainly in the functioning of such control elements.

This paper discusses the criteria that distinguish the different types of modular joints in terms of their functioning, pointing to the competitive advantage of MAURER movement joints. It will be shown that for large and arbitrary movements (e.g., due to earth quake), there is presently no alternative to MAURER swivel joints.

Fig. 1 A MAURER swivel joist joint, designed to accomodate complex movements

The Control Mechanism of Modular Joints

1. General

Depending on the support and the control mechanism of a joint, the following design characteristics can be discerned. The terms "rigid" and "resilient" hereby should not be interpreted literally, but are meant to depict a relative measure for the deformations of the respective element.

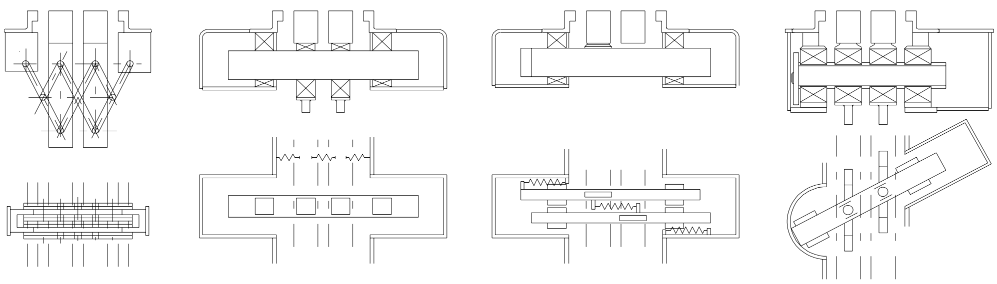
a) Vertical support of the center beam and/or the support bar
- (s..) rigid
- (e..) resilient

b) Horizontal support of the center beam on the support bar
- (..s..) rigid
- (..g..) sliding and resilient in torsion

c) Control mechanism
- (..s) rigid
- (..he) sequentially arranged and resilient support
- (..pe) parallel arranged and resilient support

A combination of such design characteristics discern the individual design types of modular joints that, as stated earlier, are mostly of proprietary nature. For example, a movement joint that is composed of the characteristics "e.s.he" shows the relevant characteristics "resilient vertical support", "horizontal support sliding and resilient in torsion", and "control mechanism sequentially arranged with resilient support". A further distinctive characteristic is the way the control elements and the support elements are located. They can be arranged both at separate locations and also functionally separated at the center beam. However for further elaborations this is only of secondary nature.

The following figure shows possible combinations of the characteristics that were pointed out above.



1 = s.s.s   2 = e.g.he   3 = e.s.he   4 = e.g.pe

Fig. 2 Functional principles of modular joints
(1 = scissor construction, 2 = sliding lamella type, 3 = MAURER girder grid type, 4 = MAURER swivel joist movement joint)

The Control Mechanism of Modular Joints

2. The control of movement joints

On the one hand, rigid control mechanisms guarantee an exact allocation of the total movement to the individual gaps, and this mechanism also employs a clearly defined support system. But on the other hand such a rigid control is prone to strains that are caused by undesigned movements, such as dimensional tolerance, difference in temperature in the respective members of the joint, and deviations from the designed movement. The support system that neither accepts dimensional tolerance nor is prestressed resiliently, gives cause to strong noise emission and high wear. For this reason, modern modular joints employ a resilient control system. Usually this is achieved by plastic springs that are either being deformed along their longitudinal axis or by means of shear deflection. The individual center beams are connected by such springs. Thus we have several chains of sequentially arranged springs. As it is the case with such a system, the total resulting stiffness is a function of the number of center beams, or modules, that are connected by this way. One exception is the MAURER swivel joist system, that is being controlled by guided and shear-resilient torsion joints. This system has all the advantages of the exact scissor control system, but, due to its shear resilience, in addition the MAURER swivel joint system can also compensate dimensional tolerances and strains. Because each center beam is controlled individually, the stiffness of the horizontal support system is independent of the number of modules, or center beams. A swivel joist system employs a control mechanism with parallel arranged springs.

2.1 The design principle of sequentially arranged springs (System "e.g.he")

By means of vertical support of the center beams, that is per each support bar, a series of sequentially arranged springs is arranged. The stiffness of each individual spring depends on the speed of its movement (i.e., is a function of the load that acts on the spring). The stiffness can be of linear or nonlinear nature. Depending on the design system of the modular joint, the control springs will be without strain, thus undeformed, either in closed state, at medium gap opening or at maximum gap opening. Because the center beams and their support bars are supported by sliding bearings, being also prestressed by sliding springs, a certain sliding resistance must be overcome to move the center beams. This sliding resistance gives rise to a so called imperfect control, that, although partially being balanced by dynamic vibrations under traffic, never can be totally ruled out.

With the springs being arranged sequentially, the system will become the weaker in horizontal direction, the more center beams a movement joint employs. This results in an increase of the imperfect control of the gap openings.

As will be shown below, we will analyse the degree of imperfect control as a function of the number of center beams. We assume the springs to employ a constant spring stiffness.

Let us assume a default opening per each gap s_0, then, as a result of a total movement w perpendicular to the edges of a joint, the new individual gap opening will be s_i.

The Control Mechanism of Modular Joints

From a certain number of center beams, the individual gaps towards the side of the abutment will only be moved if the maximum permissible individual gap opening towards the side of the bridge deck is exceeded, or, in order to prevent gap openings to exceed their maximum, stoppers will have to take care of limiting the individual gap openings to their given and preset limit.

Figure 3 shows a principle of springs that are arranged sequentially.

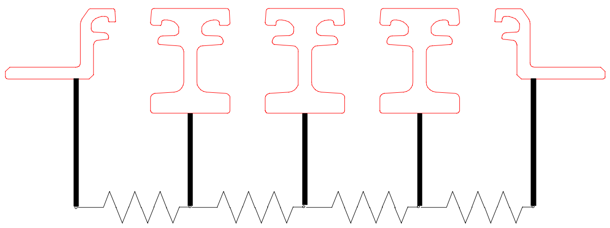


Fig. 3 Sequentially arranged control springs, general overview

The next figure shows the forces that act in the system if the bridge deck moves, with the abutment to stay put.

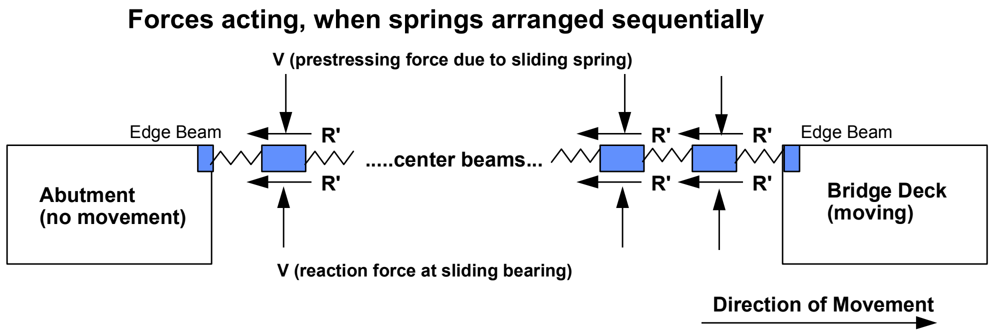


Fig. 4 Principle of the forces that act when the bridge deck moves

If the bridge deck moves, the springs in between will attempt to control the total movement in a way that this movement is equally accomodated by the gaps.

Due to the prestressing force, at each center beam (that is, support bar, respectively), friction forces R' will be triggered.

Looking at the first module (= first center beam) from the bridge deck, the situation can be shown as follows:

The Control Mechanism of Modular Joints

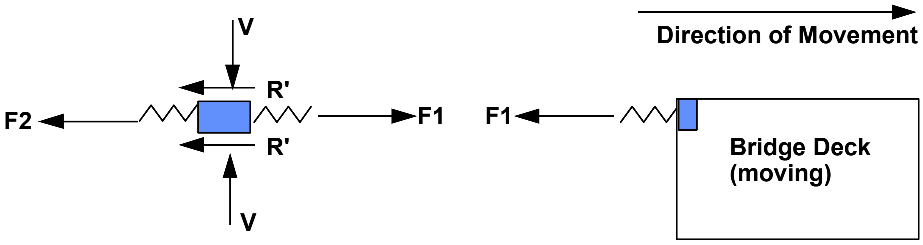


Fig. 5 Situation at the first center beam from the bridge deck side

With
R' = μ V, and , with 2 sliding plates per center beam, the total friction to be
R = 2 R'

For reasons of equilibrum, it must hold:
F2 = F1 - R, and for the 2nd center beam accordingly
F3 = F2 - R, or expressed for the i-th center beam
$F_i = F_{i-1}$ - R, and, with all R_i being equal,
$F_n = F_1$ - (n-1) R, with n being the number of gaps of a joint that participate at the movement.

Movements per gap

The total movement of the bridge deck be *w*, the number of gaps that participate at the movement be *n.* The total gap movement of a given gap will be a superposition of 2 components:

1. An equal and theoretical opening per gap of w/n
2. An imperfect control component due to friction. For each single gap, the incomplete control component *s* will be a function of the remaining spring force and the friction to take into account

To calculate the total movement per gap, that is set up by the 2 components "theoretical movement" and "imperfect movement", the following considerations have to be made:

Difference of gap width opening of 2 adjacent modules: Δs = R/c

Condition for all gaps that will move is:

$$\sum_{i=1}^{n} s_i = w$$

The Control Mechanism of Modular Joints

R depicts the friction, c the spring constant, n the number of gaps that move. Please note that n is not the number of gaps that a movement joint has, but the number of gaps that will be affected by the opening *w* of the bridge deck. In other words, part of the joint might ***not*** be subject to movement.

To calculate the number of gaps that share a given movement *w*, the condition is

w = 0.5 n (n-1) R/c, to be solved for n:

$n = 0.5 + 0.5\ \sqrt{(F + 8wc)/F}$

That is, only if *w* exceeds a certain minimum movement, then the n-th gap will start to move.

The following graph illustrates the considerations made above:

- s_o ... Gap width before movement
- w ... Movement of bridge deck
- n ... Number of moving seals
- s_{th} ... theoretical gap width
- i ... individual gap
- s_i ... gap width of individual gap
- Δs_i ... component of imperfect control
- c ... spring coefficient, linear assumption
- µ ... coefficient of sliding friction
- m ... number of sliding surfaces per center beam
- V ... Prestressing force
- R ... Sliding resistance per center beam

$$s_{th} = s_o + \frac{w}{n}$$

$$R = m \times \mu \times V$$

$$\Delta s_i = \frac{n + 1 - 2 \times i}{2} \times \frac{R}{c}$$

s_i = theoretical movement + imperfect movement, or

$$s_i = s_{th} + \Delta s_i \quad \text{and} \quad w \geq (n-1) \times \frac{n}{2} \times \frac{R}{c}$$

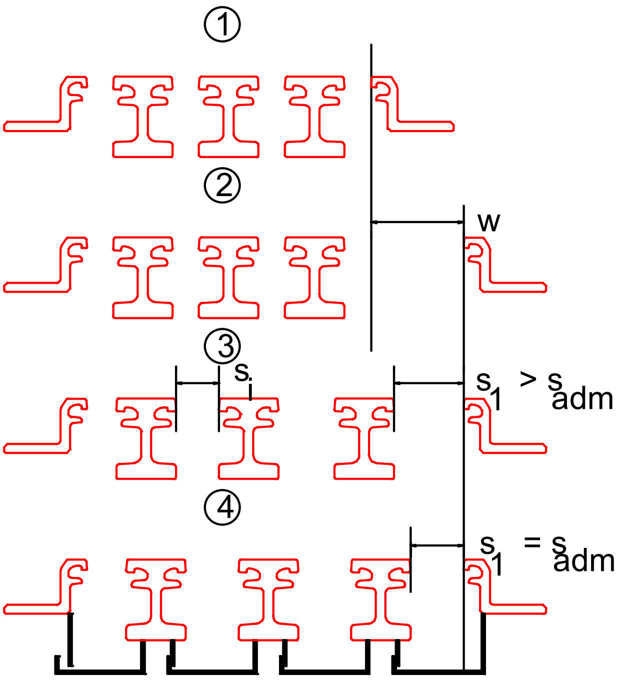


Fig. 6: Imperfect control
1 = Position before movement
2 = Relative movement of edges of joint
3 = Imperfect control without stoppers
4 = Imperfect control with stoppers

The Control Mechanism of Modular Joints

<u>Example 1</u>
The gap width control of some competitors' movement joints is accomplished by means of shear springs. Such shear springs are without strain in their so called middle-position. They experience strain when the gap opens or closes. The spring stiffness is a function of the shear modulus of the elastomer and also of the dimensions of the shear spring. The dimensioning of a shear spring has its constraints by the geometrical conditions of a joint (similar to the constraints that center beams are subject to). In other words, the stiffness of such shear springs cannot exceed certain limits. The gap width s_0 per seal before movement shall be 40mm.

As example we use an 8 seal joint.

n = 8 (that is, a maximum of 8 seals participate at a movement)

$$c = \frac{G \times A}{h} \approx 250\text{kN} / \text{m} \qquad \text{and } \tan\gamma \leq 0{,}7$$

V = 20 kN

m = 2

μ = 10 %

The following graph shows the behaviour of such an 8 seal joint as a relation of a relative movement *w*.

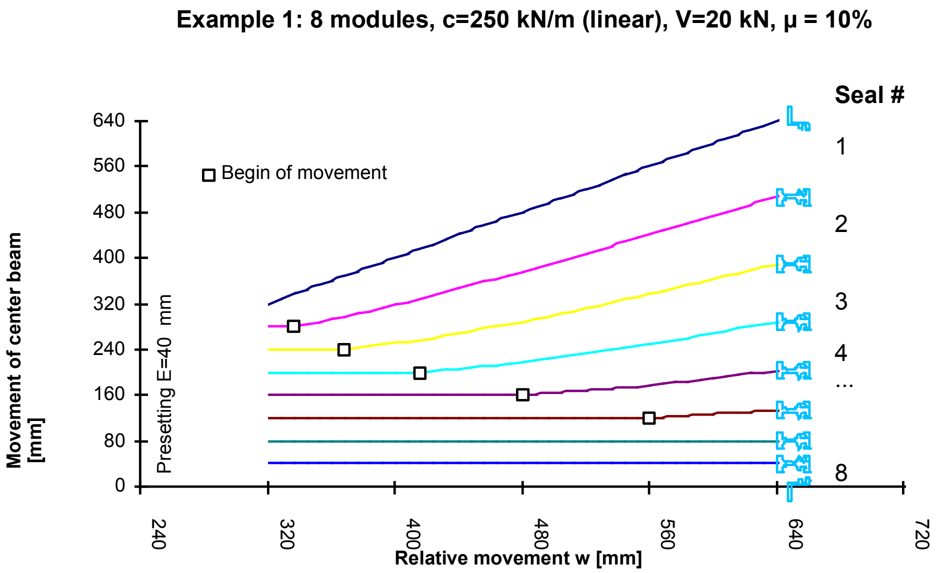


Fig. 7 Imperfect control of sequentially arranged springs, sliding lamella type

The Control Mechanism of Modular Joints

Explanation: If the relative movement is 320mm (that is, gap width per seal should increase from 40mm to 80mm), arriving at the maximum design movement of 640mm, the share of movement of the 1st seal is 133 mm, with an imperfect control component of 53mm. The 7th and the 8th seal experience no movement, that is, the remain in their original position.

If the relative movement should be only 80mm (moving from 320 to 400mm), only the first 2 center beams will experience a movement. Thus, number of seals affected is 3, and thus n = 3.
The remaining seals stay in their original position.
The small rectangles depict the amount of movement a center beam needs to be triggered to move.

<u>Example 2</u>

In using so called "stoppers", the maximum gap width can be limited to 80mm. Under the same conditions as used in the example above, the individual gap openings will be balanced to a somewhat better extent. But with a theoretical gap opening per seal of only 49mm the first stoppers will be activated and are thus subject to wear. This will be illustrated below:

Example 2: 8 modules, c=250 kN/m (linear), V=20 kN, μ = 10%

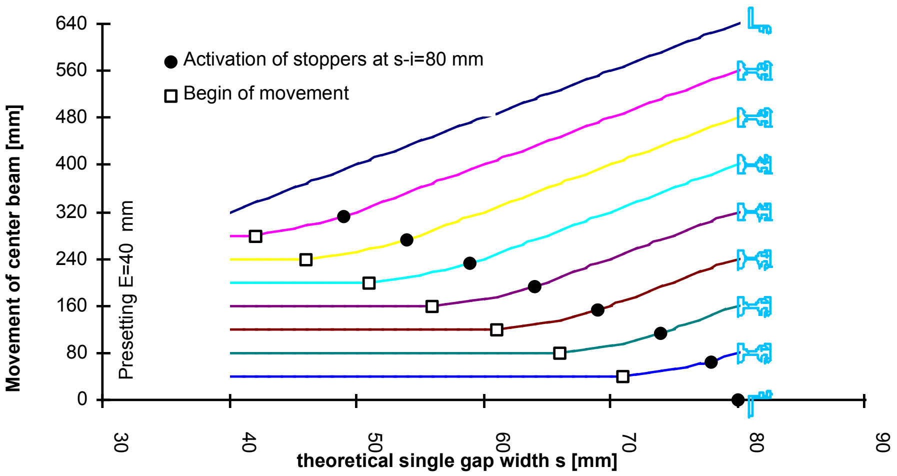


Fig. 8 Imperfect control of sliding lamella type with stoppers

Explanation:
A theoretical single gap opening of 49mm means that each of the 8 seals should have the same gap opening of 49mm. Total movement thus would be in this case 8 x (49 - 40) = 72mm. This would be the ideal case if the control mechanism would to 100% do its job, which is allocating a given movement evenly over the gap openings of a joint.

The Control Mechanism of Modular Joints

But, at the hand of the 72mm, which is the given movement of the bridge deck, the first of the seal will not just move 9mm, as it should do theoretically, but in fact moves the total remaining space of 40mm, then activating the stoppers. This reflects the reality.

We can observe 3 stages at the movement of such a lamella type joint:
- gaps that move
- gaps that have reached the stoppers, being prevented to move further
- gaps that still "wait" to be moved

During the course of the total maximum movement that a joint can accomodate, every gap rests in one of the 3 stages. Which stage an individual gap is in, depends on the location of the gap and of the total movement of the joint. Only a few of the total of 8 seals will move at a given total movement, the rest will either be prevented to move any further or is not yet triggered to move. This "phenomenon" cascades down from the first few gaps on the moving side of the bridge to the last few gaps that are situated at the side of the (firm) abutment.

Thus it becomes obvious that the behaviour of a sliding lamella joint is far from ideal, as far as the control of the gap openings is concerned.

To summarize, the above examples show that, in using the sliding lamella design of a modular joint, the maximum number of modles should be limited to 5. Stoppers that are advised to be used have to be designed to fatigue strains. But, to emphasize again, such stoppers contribute to noise emission.

2.2 Type 3 = "e.s.he", that is control of gap openings by means of sequentially arranged springs

The gap openings of MAURER girder grid joints are controlled by sequentially arranged springs. If the gap is closed, these springs are without any strain. With increasing gap opening, these control springs will be compressed. The characteristic of the spring constant is non-linear, that is, the bigger the gap opening, the stiffer the spring constant. In this respect it employs the function of stoppers.
To make it simpler, we assume here the spring constant to be constant. For a slow opening of the gap, the spring constant has a value of 400 kN/m.

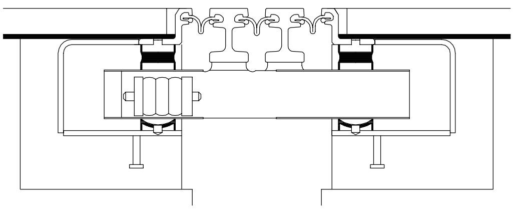


Fig. 9 Cross section of a girder grid joint

The Control Mechanism of Modular Joints

A big advantage of this system lies in the rigid connection between the support bar and the center beam, and the use of 1 support bar per each center beam. If we assume the same friction coefficients at the left and right edge of a joint, the friction forces will offset each other, and there is no imperfect control meachanism. This is independent of the pretensioning force V, spring constant c and friction. To be on the safe side, we assume that at the fixed side (abutment), the static friction μ_1 = 10%, and at the moving side the sliding friction μ_2 is around 2%. We conclude therefore

$$\Delta\mu = \mu_1 - \mu_2 = 8\%$$

A further advantage lies in the use of 2 sliding springs per center beam. As we already pointed out above, we can reduce the prestressing force of the sliding spring to 12 kN, which consequently reduces the friction force.

The figure below illustrates that all center beams will relatively early participate at the movement of the joint. The maximum gap without stoppers will be 97mm, with a difference of gap openings of 4.8mm. The stoppers that are always part of our design will be activated at the first gap only at the theoretical individual gap width
of 65mm.

Example 3: 8 modules, c=400 kN/m (linear), V=12 kN, dμ = 8%

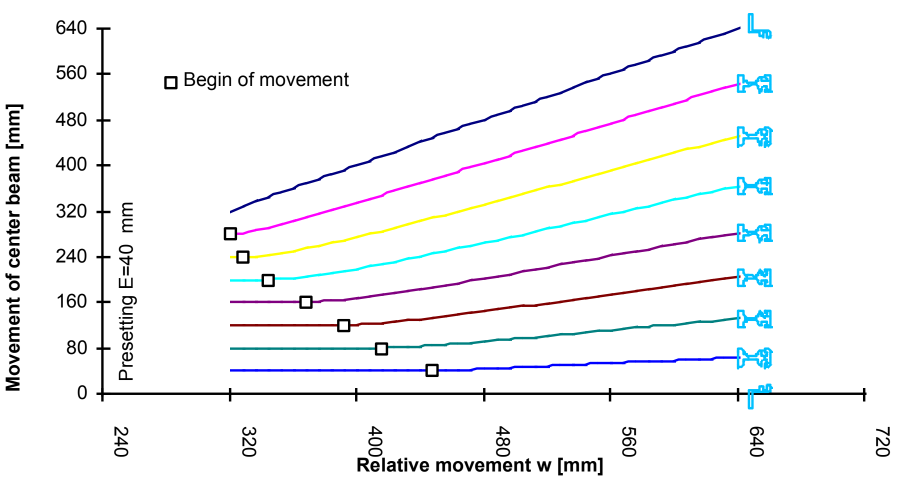


Fig. 10 Imperfect control of MAURER girder grid joints

As a result we can maintain that MAURER girder grid joints are suited for a modular joint of a maximum of 8 modules.

The Control Mechanism of Modular Joints

2.3 Type 4 = "e.g.pe", control mechanism with parallel arranged springs

The MAURER swivel joist joint is the only system that employs a control mechanism of the center beams with parallel arranged springs.

Due to the specific arrangement of the support bars as well as the connection between support bar and center beam, both the load carrying function and the control function can be achieved in a simple way, without need of a specific control mechanism.

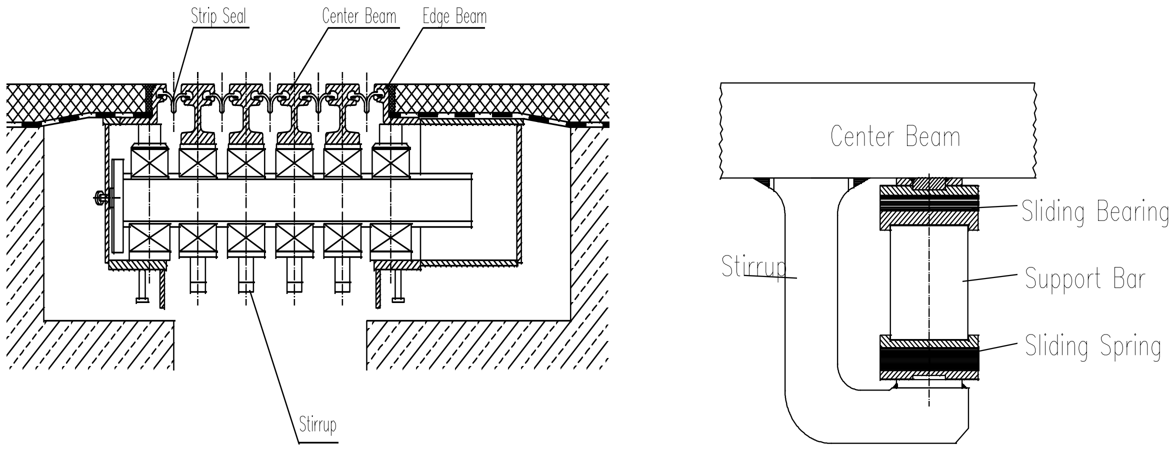


Fig. 11 MAURER Swivel Joist Joint

The center beams will be supported by the support bar allowing sliding along the axis of the support bar. They rest on shear-torsion-sliding elements with guidance elements along the support bar. The support elements are supported at the center beam and at the support stirrup respectively, allowing torsion around their vertical axis. Thus, their distances are fixed.

If the superstructure moves, the support bars will be pushed through the swivelling guiding bearings and thus experience a swivel movement. Due to the fixed distances of the torsion elements, this swivel movement gives rise to an almost even allocation of the total movement to the individual gap openings.

The control mechansim of MAURER swivel joist joint employ all advantages of an exact push and pull control. But in addition this MAURER design can also compensate undesigned, or unwanted, movements like dimensioning tolerances in manufacturing, or different deformation of the edge beam and the center beams due to temperature differences. This can be owed to the shear-resilient torsion joints.

The Control Mechanism of Modular Joints

The shear resilience of the support elements affects a certain incomplete control of the individual gaps. This effect can be offset with the help of shear-rigid support elements at the edge beams, which then leads to an exact control mechanism. The incomplete control is independent of the number of modules.

This will be pointed out below:

If the support bar is situated in the original skew position β and will swivel due to a movement w with an additional angle α, at the hand of a shear-rigid support the i-th sliding bearing would receive a movement w_i. Because of prestressing that leads to friction in the sliding areas, a resulting friction force R must be overcome. However, due to a swivel movement of the support bar by the angle α_i the sliding bearings will receive shear stresses until the component S_p that acts parallel to the support bar offsets the friction force R. In other words, only by a certain minimum angle α_i the center beam will be moved.

The following conditions hold:

$$S = (c_L + c_F) \times 2 \times v \times (n - i) \times \frac{\sin\left(\frac{\alpha}{2}\right)}{\cos(\beta)}$$

$$S_p = S \times \frac{\cos\left(\frac{\alpha}{2} + \beta\right)}{\sin(\alpha + \beta)}$$

$$\alpha = \alpha_i \qquad \text{für} \qquad S_p = R = 2 \times \mu \times V$$

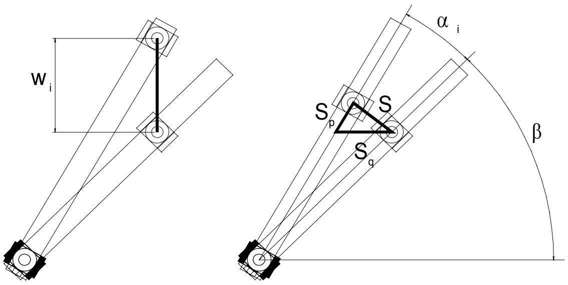


Fig. 12 Control of sliding elements of MAURER swivel joist joints

and

S... Shear force due to strain of the sliding elements
C_L... Shear stiffness of the sliding bearing
C_F... Shear stiffness of the sliding spring
v... Displacement of the support of 2 adjacent center beams in longitudinal axis of the joint
n... Number of sealing elements
i... Support to be pointed at
α.. Swivel movement of the suport bars
β... Original position of the support bar
S_p.. Component of S parallel to the support bar
α_i... angle, for which holds: $S_p = R$
R... Friction force of each suport element
μ... coefficient of friction
V.... Prestressing force acting in the sliding areas

The Control Mechanism of Modular Joints

Fig.13 shows the behaviour of a swivel joint of 4 modules at the time where $S_p = R$ at the 4th support. It will be shown that the gap s_4 and the position of the 3rd center beam is still not yet moved, whereas the 1st center beam has moved by the value $w\text{-}s_1$ and the 2nd center beam has moved by the value $w - s_1 - s_2$. Fig. 11 shows that that the gap width s_2 to s_{n-1} are almost of the same value. The imperfect control that occurs at gap s_n must be compensated at gap s_1. As a result, only the 1st gap and the last gap are subject to imperfect control, and this is independent of the number of modules, be it 2 modules or 25 modules.

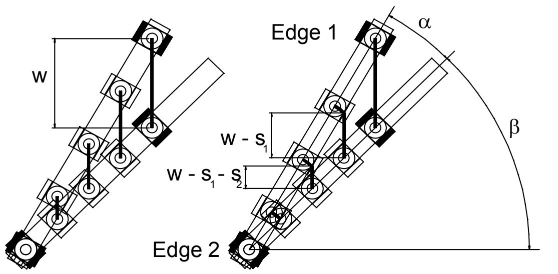


Fig 13 Control of a 4 modules joint having shear-rigid (left) and shear-resilient (right) support system

To compare this design type of a swivel joint, we will illustrate the mechanism of imperfect control with the help of actual design parameters.

$n = 8$, $C_L = 1{,}000$ kN/m, $C_F = 500$ kN/m,
$V = 20$ kN, $\mu = 10\%$, $s_0 = 40$ mm, $v = 90$ mm

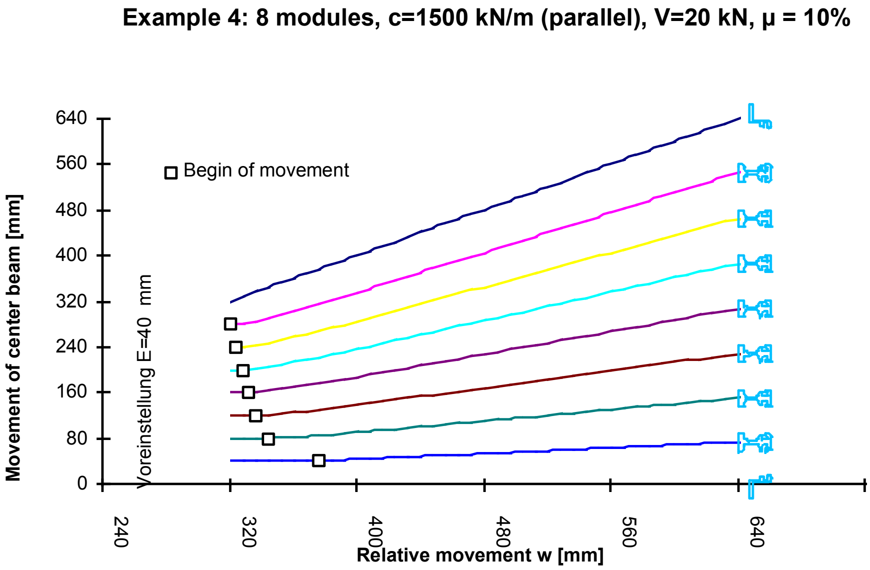


Fig. 14 Imperfect control of MAURER swivel joist joints

The figure above illustrates this behavior of a imperfect control. If each gap experiences a theoretical movement of 4mm, 7 of the 8 center beams are activated. When the 8th center beam is activated, the imperfect control at the 1st center beam is 11mm. This value remain almost constant up to the total opening of all gaps.

2.4 Summary

The essential characteristics of the 3 control systems described in this paper are summarised in Table 1. Fig. 15 shows the individual gap openings at the time of the maximum opening of the movement joint, according to the examples 1, 3 and 4.

The numbers between the profiles reflect the respective deviation from the expected ideal value and thus indicates the amount of imperfect control of the respective center beam.

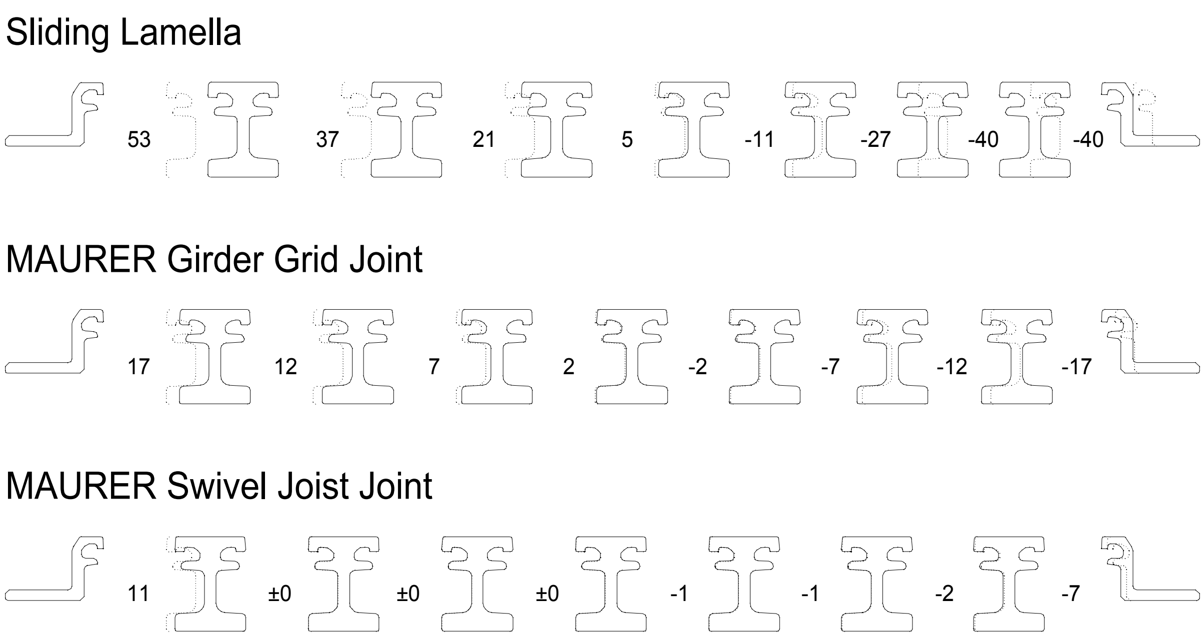


Fig. 15 System comparison at maximum gap opening

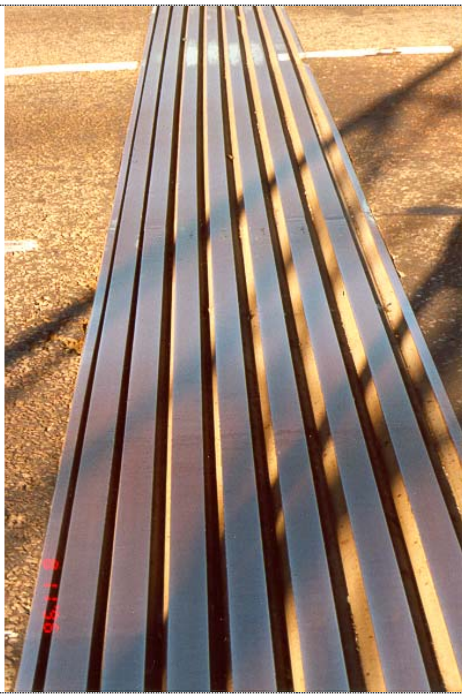
The Control Mechanism of Modular Joints

Overview of design characteristics

Sliding lamella	Girder Grid Joint	Swivel Joist Joint
• sequential control mechanism	• sequential control mechanism	• parallel control mechanism
• maximum number of elements ~5	• maximum number of elements ~8	• unlimited number of modules
• direction of movement fixed	• direction of movement fixed	• direction of movement arbitrary
• Large control problems, increasing with number of modules	• Medium control problems, increasing with number of modules	• Little control problems, independent of number of modules
• Stoppers required	• Stoppers required	• Stoppers not required
• Failure of 1 control spring inhibits total control of gap openings	• Failure of 1 control spring inhibits total control of gap openings	• Failure of 1 sliding bearing affects only the respective center beam and not the total system
• High friction force due to high pretensioning (V = 20 kN) and summation of the sliding surfaces (μ ~ 10%)	• Little friction force due to double support (V = 2 x 12kN) and the their partially balancing effects (Δμ ~ 0-8%)	• High friction force due to high pretensioning (V = 20 kN), however only 1 pair of sliding elements (spring and bearing)
• Default position of sequentially arranged springs is in middle position, there being without prestressing, and consequently being subject to vibrations	• When gap is closed, control springs are without strain. Prestress starts with gap opening. The bigger the opening, the more the stabilising effect of the control springs	• No sequential chain of springs. System is stabilised independently from number of modules and size of gap opening
• Spring constant (stiffness) low and of linear nature. Stoppers will be activated at an early stage, thus leading to emission of noise	• Spring constant (stiffness) in the middle range and of nonlinear nature. If gap opens, control springs get increasingly stiff and so support the stoppers.	• High spring stiffness, and also high stiffness of the system, particularly for large movement joints.
• Transmission of horizontal forces dependent on number of modules. The higher the number of modules, the weaker the total system, leading to large movement of center beams. Horizontal force must be transferred via the spring chain.	• Transmission of horizontal forces dependent on number of modules. The higher the number of modules, the weaker the total system, leading to large movement of center beams. Horizontal force must be transferred via the spring chain.	• Transmission of horizontal forces independent on number of modules. Horizontal force will be transferred from the center beam via the support bar directly to the edges of the joint.
• Permissible spacing of support bars depending on number of modules	• Permissible spacing of support bars depending on number of modules	• Permissible spacing of support bars independent of number of modules (STP system)
• Tilt-resilient support with high strain onto the sliding bearing	• Tilt-rigid support by means of a stiff connection, resulting in little strain onto the sliding bearing	• Tilt-rigid support by means of a pair of forces acting in the guidance of bearing and springs, resulting in a medium strain onto the sliding bearings

The Control Mechanism of Modular Joints

ENCLOSURE 1

Control mechanism of MAURER swivel joist expansion joints	
Control mechanism of sequentially arranged springs	

The Control Mechanism of Modular Joints

ENCLOSURE 2

Tsing Ma Bridge **Hongkong** **5 March 2001** **1:30 p.m.**	
Tsing Ma Bridge **Hongkong** **6 March 2001** **3:00 a.m.**	
Tsing Ma Bridge **Hongkong** **6 March 2001** **4:30 a.m.**	

The Control Mechanism of Modular Joints

A typical example that confirms in practise what the theory of this paper wants to convey is the Tsing Ma Bridge in Hongkong, where a 25 seal modular joint of type „sliding lamella“ was installed. According to the theory presented here, friction in the control mechanism of a sliding lamella type would be that large that control of the gap width can no longer be guaranteed for all gaps. Rather, only the modules next to the moving bridge deck will move, and the center beams (i.e. modules) further away from the action will not be subject to any movement (In this respect pls. refer to our *Fig. 15*, that shows, among others, the theoretical movement of a sliding lamella of 8 seals, illustrating that in this example gaps no. 7 and 8 did not move at all. Hereby, the deviation „-40“ in *Fig. 15* means that instead of the resulting gap opening of 80mm the gap remained at 40mm, which was its initial position).

Now, take a look at this 25 seal joint (page before). The gap openings were photographed in the afternoon at 1.30pm, and then again twice in the night, at 3.00 am and 4.30 am:

- Gaps close during daytime (thermal extension of the bridge deck). Clearly it can be seen that the first 3 gaps, counting from right, are totally closed. Gap #4 is partially opened.
- 13 ½ hours later, at 3 a.m., due to thermal contraction of the bridge deck the gaps open. Again, this applies only to the first 3 gaps, and the 4th gap already remains at its position that it had during daytime, and same it is with all gaps further left.
- Another picture was taken at 4.30 am, the (probably) coldest time of a day. This picture shows that now gap #4 also opened up to some extent, but gap #5 and all other gaps further left do not appear to have undergone any movement.

This real case confirms our theory that for large movements only swivel type joints are adequate, if equal opening of gap widths should be desired. This showcase also points to another weakness of a sliding lamella type at large movements: system stiffness in horizontal direction is too weak, and equal gap openings cannot be maintained. Thus, the gap openings by and large are arbitrary. In case of a sudden horizontal force acting onto the lamella type joint, like for example a braking force, the system cannot transfer the horizontal loads without large and sudden movements of the lamellas. In addition, the following consequences have to be taken into account if only a part of the gaps move. In this case:

- Every day the first 3 or 4 gaps have to cater for the daily movement of perhaps 250mm in each direction. This means that every day these gaps have to totally open and close, thus performing a movement that normally only should occur during the course of a whole year.
- In order to limit the gap width, the gap width stoppers have to be activated every day, and consequently they should be designed to fatigue (which they probably are not, assuming the manufacturer’s claim that the system should work properly)
- Also, the sliding area that caters for the movement of these first 3 or 4 gaps is subject to considerable wear.

All this additional wear at a concentrated area of the joint can be translated to additional maintenance costs for the owner of the bridge, since he will have to closely observe the performance of this lamella joint, making sure that the joint is safe for passing traffic.