Technical note

Rotation of supporting small bearing pads in buildings

Denis Camilleri of DHI Periti, Malta provides a follow-up to his previously published technical note (Vol.89 Iss.5), this time on the subject of calculating the rotational forces on bearing pads

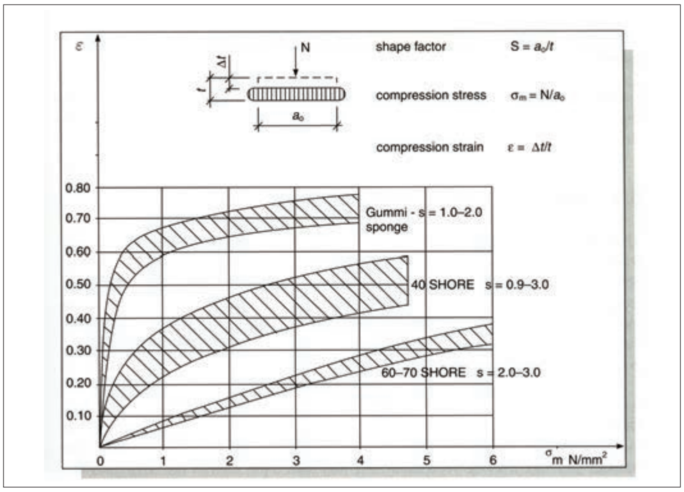
The author's previous technical note[1] dwelt on deflection and vibration effects as these relate to the building inconveniences caused. Various ratios were then discussed, outlining methods that may easily be adopted in design offices to engage on a particular ratio considered to cause least disturbance for the use/s anticipated.

This note demonstrates that it is an even easier step to go from a deflection span ratio onto a rotation calculation, as a simple relation connects these criteria.

Materials used for bearing pads include:

- Chloroprone (neoprene); probably the most popular
- Laminated elastomeric pads with reinforcing layers of steel or fibreglass, generally used for bridge bearings
- Steel plates mostly used as shims
- Low friction material such as Teflon® or plastic membrane strips are used to provide a slip surface, mostly used under hollow core slabs

A number of materials such as bituminous joint filler, hardboard, wood and similar filler materials have been used, but these are not considered as structural materials.



1 **Strain vs stress relationship for bearing pads of different hardness (Source: *Kim S. Elliott, Precast concrete structures*[6]. © *Elsevier*)**

Reference to rotations in standards

If deflection and vibratory effects are engaged at some stage of the design process, less and less is catered for in the rotations arising at the bearings of structural elements. Details may be found in the CIRIA Technical Note[2] which refers to rotations and quotes quite small rotations or changes of section at the supports (such as occur in reinforced concrete because of cracking) cause relatively large increases in deflection. It is then suggested that sliding and movement joints may thus be necessary to avoid cracking and rotation for brickwork construction. A movement detail for a precast element then notes that a shortening in bearing length, further compounded by translation due to rotation could lead to serious shortcomings. However, further to a suggestion not to rely on full fixity in calculating deflections no further concrete guidance is given on allowable rotations, just prudence advocated.

BS 5400-9.1:1983 relating to Bridge Bearings refers to rotational limitations as outlined in the following expressions:

For plain pad and laminated bearings, the total vertical deflection, D, should satisfy the expression

$D > (b_e\alpha_b + l_e\alpha_l)$ ...1

For strip bearings, the total vertical deflection, D, should satisfy the expression

$D > b_e\alpha_b/3$ ...2

Where:
b_e is the effective width of the bearing
l_e is the effective length of the bearing
α_b is the angle of rotation across the width, b, of the bearing (in radians)
α_l is the angle of rotation (if any) across the length, l, of the bearing (in radians)

It is further stated that plane-sliding bearings normally provide for translation only. Rotation can be permitted in accordance with flat sliding surfaces and should not be used to accommodate rotation other than about an axis perpendicular to the plane of sliding. Other provisions should be made for rotation about an axis in the plane of sliding.

BS 8110 notes that when large rotations occur, without defining what is large, suitable bearings should be used. Reference is then made that these rotations may throw the line of action onto the outer face, necessitating larger bearing stresses. EC2 refers to where a beam or slab is continuous over a support which may be considered to provide no restraint to rotation (e.g. over walls), the design support moment, calculated on the basis of a span equal to the centre-to-centre distance between supports, may be reduced by an amount as follows:

$\Delta M_{Ed} = F_{Ed,\,sup}\ t / 8$ ...3

Where:
$F_{ed,sup}$ is the design support reaction and t is the breath of the support.

The alloweable plastic rotation is then given at 0.015rad and 0.035rad varying on the grade of concrete and steel adopted. Again EC0 *Basis of Structural Design* quotes rotations varying within the same limits. EN codes on bearings make various references to rotations, however specific and clear criteria may be gleaned from a PCI report[3], where a simplified method catering for rotation in bearing pad design is suggested. The report noted that most codes related to large bridge bearings with small pads

Slab depth mm	Safe loading kN/m²	Span/Total deflection ratio	Span:Depth ratio	Rotation at support in radians
250	15	1:307	26.00	0.0104
330	30	1:395	19.70	0.0081
450	55	1:588	14.45	0.0054
500	72.5	1:667	13.00	0.0048

Table 1 Prestressed transfer planks deflection/rotation characteristics

Deformation	Due to compressive load – mm (A)	Due to rotation (rad) – internal environment – mm (B)	Maximum deformation at leading edge of seating – mm (A + B)	Minimum deformation at rear edge of seating – mm (A – B)
500mm deep unit – internal environment	1.05	0.45	1.5	0.6
500mm deep unit – external environment	1.05	1.125	2.175	–0.075
250mm deep unit –internal environment	0.30	0.56	0.86	–0.26
250mm deep unit – external environment	0.30	1.35	1.65	–1.05

Table 2 Deformation of bearing pads under varying climatic conditions

required in buildings regulated to a secondary position. The objectives of the report were to develop adequate design criteria for precast concrete buildings. A common rule of thumb is quoted at:

$R = 2D_c/L$ ...4
Where: R rotation is given in radians
D_c is the compression displacement
L is the length of bearing in direction of rotation

On the assumption that a minimum displacement of 0.15t occurs under design load, the above rule of thumb equation becomes maximum rotation in radians = $R < 0.3t / L$ ...5
Where:
t is the pad thickness
L is the direction of the pad taken in either of one of the principal dimensions where the rotation occurs.

This PCI publication[3] further recommends that the length and width of the unreinforced pad should be > 5 thickness for stability. The thickness t should be > 6mm for stemmed members and >10 mm for beams. Unreinforced pads with shape factor S < 2 should be avoided for 'tees' and S < 3 avoided under beams.

The shape factor S is a means of taking account of the shape of the elastomeric layer in strength and deflection calculations. It is the ratio of the effective plan area of an elastomeric slab to its force-free bulging surface area, including holes.

For plain pad bearings, the shape factor S is given by the expression:
$S = A / (l_p \times t_e)$ ... 6

For strip bearings the shape factor S is given by the expression:
$S = a / (2 t_e)$ ...7

Where:
A = the overall plan area of the elastomeric bearing
a = the overall width of the strip bearing
l_p= the force-free perimeter of the bearing including that of any holes if these are not later effectively plugged
t_e = the effective thickness of an individual elastomeric layer in compression

The shape factor defines how thin the layer is compared with its lateral dimensions. For an infinitely wide strip bearing, W is infinite and S = L/2t. ...8

For a square, S = L/4t, ...9

and for other rectangular shapes, S lies between these two bounds.

Common bearings have S in the range 3 < S < 8. The shape factor also provides a useful basis for normalising the compressive stress, σ, since the shear strain caused by compression is, according to small displacement theory, directly proportional to σ/GS, where G is the shear modulus of the pad material.

Increasing the shape factor S therefore increases the axial stiffness and strength, but it reduces the ability of the bearing to accommodate rotation. These opposite tendencies may cause a dilemma in design. A larger bearing with a higher shape factor would carry the axial load better, but it would reduce the bearing's ability to accommodate rotations. It is worth noting that such design involves the use of a mixture of force and displacement loadings and that this combination presents challenges. The axial load is a force yet the rotation is a displacement. Designing for both simultaneously requires that the bearing be stiff in compression yet flexible in rotation. That may be difficult, because the features (size, shape factor) that make it stiff in compression tend also to make it stiff in rotation.

Support rotation calculations

For a uniformly distributed load w acting on a simply supported girder of effective span l, the end rotation θ is
$\theta = (wl^3/EI)/24$ ...10

And the mid-span deflection divided by the span length, the span deflection ratio Δ/l, is
$\Delta/l = (5wl^3/EI)/384$ ...11
Where EI is the flexural rigidity of the structural material.

The ratio between equations 10 and 11 works out at:
$\theta/(\Delta/l) = 1/24/ (1/384) = 3.2$ ...12

Similar calculations for a single concentrated load at mid-span give a ratio of 3.0. The end rotation consistent with a udl deflection of l/800, is given at: $\theta = 3.2 / 800 = 0.004$rad.

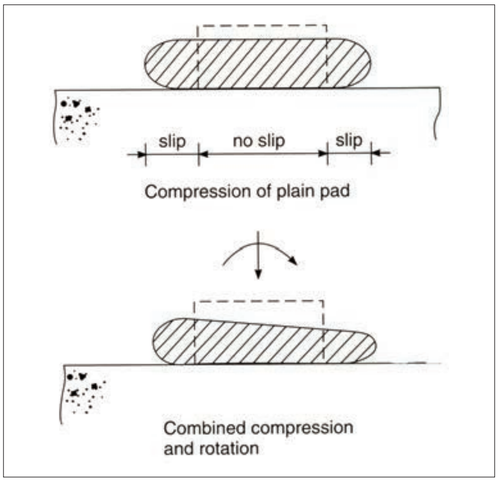
The end rotation for any other deflection limit can be obtained directly by scaling.

For continuity over two or three spans, the mid-span deflections and the end rotations (at the central support) are multiplied by factors as obtained from reference literature[4]. Because in multi-spans the end rotation decreases more than the mid-span deflection, the net effect is to reduce the end rotation if the mid-span deflection is still controlled by the l/800 limit. If the entire load is treated as distributed, the largest possible end rotation is (0.50/0.70) × (0.004) = 0.00286 radians for two spans, and (0.40/0.52) × (0.004) = 0.00308 radians for three spans.

Calculations then compile an (amplified) rotation comprising:

Allowance for uncertainty:	0.0050
Thermal camber:	0.0015
Loading:	0.0040
Total:	0.0105 rad

In particular, the allowance for uncertainty is a very small angle given as 0.005 radians, This corresponds to a movement from center of about one tenth of the bubble length in a carpenter's



2 **Behavior of elastomeric bearing pads. (Source: *Kim S. Elliott, Precast concrete structures*[6]. © *Elsevier*)**

level. Thermal effects can cause camber in the superstructure. It is typically largest when the sun shines on the roof deck, which absorbs radiant heat and expands, with its effect being comparable or even larger than that of the applied loading. Protected intermediate floors will be subjected to a smaller overall rotation given at: 0.0105 – 0.0015 = 0.009 rad.

Reference is being made to Table 2 in the previous Technical Note published in *The Structural Engineer*[1]. This is reproduced here as Table 1, with the additional final column referring to rotation at support in radians. This column is obtained as noted from equation 12 by dividing the 3.2 constant with the span/total deflection ratio as obtained from column 3 in Table 1.

The rotations quoted in Table 1 note the largest rotation at 0.0104rad as obtained from the 250mm shallowest depth with however, the lowest load capacity at 15kN/m². The lowest rotation at 0.0048rad is obtained from the highest section depth 500mm, having the highest load capacity at 72.5kN/m².

The amplified rotation, as above for these sections is given at:

225mm section depth 0.005 + 0.0150 + 0.0104 = 0.0304rad
500mm section depth 0.005 + 0.0150 + 0.0048 = 0.0248rad

These rotations are noted to both lie within the alloweable rotation limit as quoted above, between 0.015 and 0.035rad.

There surely must lie a correlation between the imposed bearing rotation and the bearing stress block shape? Whether the stress block is rectangular, triangular or even parabolic in shape it must be dependant on the rotation of the supporting member.

Design of bearing pads

The amount of bearing length required for a precast floor element is relative to a number of considerations including span, loading and type of support. Detailed requirements of bearings for precast slabs are contained in Clause 5.2.3 of BS 8110 and take account of bearing stresses, possible spalling of support and of the supported member, and construction inaccuracies.

For example, for the above 250mm slab of 6m span and supported on a masonry wall the nominal design bearing value is:

Min. bearing related to bearing stress (Clause 5.2.3.2)	12.5mm
Spalling of masonry support (Clause 5.2.3.7.2)	25mm
Spalling of end of precast slab (Clause 5.2.3.7.3)	Nil
Allowance for construction inaccuracies (Clause 5.2.4(b))	24mm
Total bearing length	61.5mm

As a minimum bearing length of 75mm is specified if bearing on steelwork or concrete of minimum Grade 30, whilst on masonry this is given at 100mm[5]. Thus, this bearing length of 100mm is to be adopted. Similarly, for the 500mm deep section the bearing length works out at 110mm. The above minimum bearing lengths give an idea of where a steel flange not less than 180mm is desired for supporting precast slabs on both sides.

For a Shore hardness 60 elastomeric strip bearing pad of 90mm depth and 6mm thickness:
Shape factor S as per equation 7 given at: 90/(2 x 6) = 7.5
compressive stress on pad for the 500mm unit on a 6m span works out at: 72.5kN/m x 3m / 0.09m = 2.4N/mm².

For this compressive stress, Fig 1 outlines a strain as imposed on the elastomeric pad of 0.175. This imposes a compression (column A Table 2) on the bearing pad of the 500mm deep unit given at: 0.175 x 6mm = 1.05mm

Similarly for the 250mm unit the compressive strain works out at: 15kN/m x 3m / 0.075m = 0.6N/mm².

For this compressive stress, Fig 1 outlines a strain as imposed on the elastomeric pad of 0.05. This imposes a compression (column A table 2) on the bearing pad of the 250mm deep unit given at: 0.05 x 6mm = 0.3mm

PCI equation 5 limits rotation to: 0.3 x 6 /90 = 0.02rad.

This is less than the rotations quoted above at 0.0248 and 0.0304rad for the above precast 500mm and 250mm deep sections. On the other hand, if these precast units are internal units not subjected to thermal strains, then the respective rotations are reduced to 0.01rad and 0.015rad respectively and considered acceptable.

Where the rotation θ is known the deformation $\Delta t = \pm 0.5 b\theta$ ...13

(Fig 2 notes the positive value at the leading edge and the negative value at the rear edge of the pad – given in column B Table 2), where b is depth of the relative bearing strip and θ in radians is defined and calculated as above.

Table 2 gives the results of the maximum and minimum deformations occurring on the bearing strips for precast units of 250 mm and 500mm respectively for the safe loads as noted above and placed in varying environment settings.

Table 2 notes that the leading edge of the bearing is always under compression for all types of conditions. This is not so for the rear edge, which is lifting off where the bearing occurs. For the 500mm unit this lifting occurs solely when subjected to temperature variations, whilst for the 250 unit this occurs for the internal and external environments.

Now it is known that various crack patterns occur to roof top constructions when concrete and concrete blockwork are used in combination, The concrete slab slides over the supporting blockwork with the resulting, generally horizontal crack pattern formation sometimes even extending up to four courses below the seating level of the concrete slab. This cracking has always been advocated as arising due to the thermal movements occurring. Noting the Table 2 results, it appears that the rotation of the seating bearing has a greater say in the creation of the crack patterns formed.

With respect to the uplift created for the 250 unit at –0.26mm in an internal environment, this crack pattern that might arise is not normally visible. The loading from the overlying floors, if great enough, cancels out any uplift that tries to develop.

The above calculations for the elastomeric bearing pad are taken from the literature[6].

Dry pack mortar for bearings

As noted above an elastomeric strip bearing has adequate rotational capacity at the support. What can however, be stated for dry pack mortar with respect to its rotational capacity?

Reference is made to a paper[7] dwelling on mortar properties as bearing materials. Here, it is suggested that mortars in light weight material have a better rotational capacity. Tests carried out on samples indicate that these mortars work satisfactorily for semi-rigid design.

Epoxy mortars are known to develop compressive strengths after 28 days of $90N/mm^2$ and have been adopted as bridge bearings. However, possibly such epoxy materials will be too rigid to take the support rotations imposed. Repair mortars with a build up of fibre-reinforced powder mix and modified styrene butadiene latex gauging liquid gives a 28 day strength of $22.5N/mm^2$.This may be considered more flexible, noting as above that, the bearing stresses under direct load is achieved at $2.4N/mm^2$. Should lightweight repair mortars (as suggested in the paper[7]) be taken into consideration?

Conclusions and recommendation

An easy relationship exists, noted in equation 12, to convert span to deflection ratios by a constant 3.2 to rotations in radians. However, it is noted that unlike major bridge structures, relatively little importance is given to the rotation bearing seating capacity for buildings. The effect induced by rotations was noted to increase for exposed structures, with increased rotations noted for lighter sections, even though subjected to much lighter loadings. This as evidenced from results noted in Table 2.

Crack patterns have been known to exist for roof structures and possibly attributed to thermal and shrinkage cracking. The placing of a plastic sheet material prior to the casting of a concrete slab has been advocated in order to mitigate crack formation. This detail has not always been successful and the above demonstrates that there exists more than just thermal movement, with rotation at the support being the major cause for this cracking.

Possibly the dry pack mortars that are being specified as seating bearings are too rigid, not providing sufficient flexibility for rotation to occur. This in turn relates to spalling of the supporting section, eventually resulting on exposing the reinforcement. The deterioration then sets in, necessitating structural repair jobs. More research and testing on the specification of a dry pack mortar, together with outlining the shape of the resulting bearing stress block are presently called for.

References

1. Camilleri, D: Technical Note 'Deflection and preliminary vibration effects on structural elements' *The Structural Engineer*, 1 March 2011, **89**/5, p 17/18
2. 'Design for Movement in Buildings', *CIRIA Technical Note 107,* 1981
3. 'Criteria on the Design of Bearing Pads', *PCI Technical Report No 4*,1985
4. 'Rotation Limits for Elastomeric Bearings', *National Cooperative Highway Research Program (NCHRP) report 596*, 2008
5. Technical Note, Precast Flooring Federation, 2005
6. Elliott, K. S.: *Precast concrete structures,* Butterworth-Heinemann Publications, 2002
7. El Debs, M. K., da Silva Ramos Barboza, A. and Miotto, A. M.: 'Development of material to be used for bearing pad in precast concrete connections', *Structural Concrete,* 2003