A THEORETICAL AND AN EXPERIMENTAL INVESTIGATION IN THE TWISTLESS BEHAVIOUR OF SLAB-BEAMS PANELS

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Résumé

Une analyse par éléments finis, en utilisant le logiciel PAFEC, a été effectuée sur un panneau de dalle interne, de forme rectangulaire, uniformément chargé et continu sur un réseau de poutres, et également sur un panneau de dalle similaire mais singulier, en considérant plusieurs rapports de portée et plusieurs relations de rigidité reliant les poutres adjacentes. L'objectif a été la détermination des valeurs des rapports de rigidité des poutres adjacentes (γ_1-γ_2) pour lesquelles la distribution des moments fléchissant à travers, la dalle, dans ses deux directions orthogonales, est uniforme, ainsi que la distribution des charges transmises aux poutres d'appui. Ces cas particuliers dans leur comportement structurel, identifiés comme les cas non-torsionels, peuvent être exploités pour élaborer une alternative dans le calcul des panneaux poutres-dalles. Plusieurs modèles réduits, caractérisés par des rapports non-torsionels poutre/dalle, ont été testés pour déterminer leur comportement sous l'action d'une charge uniformément répartie. Les résultats de ces tests sont présentés et comparés aux valeurs théoriques.

***Mots clés**: dalle, rapport de rigidité poutre/dalle, rapport de portée, comportement non-torsionel, modèles réduits.*

Abstract

A finite element package PAFEC was used to analyse both an internal panel of a uniformly loaded slab continuous over a rectangular grid of beams simply supported at their intersections, and a similar but single panel for various aspect ratios and various adjacent beam stiffness relationships. The object has been to determine values of the adjacent beam/slab stiffness ratios (γ_1-γ_2) for which the distribution of the bending moments across the slabs in the two orthogonal directions is uniform, as is the load distribution on the supporting beams. These particular cases of structural behaviour, identified as the twistless cases, could be exploited for developing an alternative design procedure for slab-beam systems. Several small scale slab-beam models with twistless beam/slab ratios have been tested to determine their behaviour under the action of a uniformly distributed load. The test results are presented and compared to the theoretical values.

***Key words**: slab, beam/slab stiffness ratio, aspect ratio, twistless behaviour, small scale models.*

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ملخص

استعملت طريقة العناصر المتناهية لبرنامج *PAFEC* لإجراء دراسة تحليلية على بلاط داخلي مستطيل يحتوي على حمولة موزعة و مستمر فوق شبكة من العتبات، و كذا على بلاط مماثل لكن منفرد، باعتبار عدة عوامل للأطوال و عدة علاقات تربط جساءات العتبات المتجاورة. إن الهدف من هذه الدراسة هو الحصول على مختلف قيم عوامل الجساءات المتجاورة عتبة/بلاط (γ_1-γ_2) حيث يكون توسيع عزوم الإنحناء بتقاطع البلاط في اتجاهه ثابت و كذلك الأمر بالنسبة لتوزيع الحمولة على العتبات الحاملة. هذه الحالات الخاصة للسلوك الهيكلي، المشار إليها بحالات اللاإلتواء يمكن استغلالها لتطوير بديل لحساب هياكل متكونة من البلاطات-العتبات. أجريت تجارب على عدة نماذج مصغرة ذات عوامل عتبة/بلاط لاإلتوائية لتحديد سلوكها تحت تأثير حمولة موسعة. وتمّ النتائج التجريبية المحصلة عرضها و مقارنتها مع النتائج النظرية.

***الكلمات المفتاحية:** بلاط، معامل الجساءة عتبة/بلاط، معامل الأطوال، السلوك اللاإلتوائي، نمادج مصغرة.*

Although there is clear evidence from many experimental and theoretical investigations [1-4] that the moment pattern in slabs and investigations [1-4] that the moment pattern in slabs and beam bending moments are significantly affected by changes in supporting stiffness, it is still customary to design slab and beams as though they were independent elements. An extensive study of elastic full composite action in slab-beam systems has been carried out for both single and internal rectangular panels [5]. The finite element package PAFEC [6] was used to assess the structural response of these panels subject to an overall uniform load. Both the ACI(318-89) Direct Design Method [7] and the BS8110 slab design [8] were used for comparison purposes. The results obtained reveal many interesting aspects of full composite action often ignored in current design practice. However, they clearly indicate that the development of a slab design method coping with any beam/slab stiffness ratio is an extremely difficult task. Moreover, it was also evident that the non-incorporation of important factors, such as the relation between beam stiffness in the two orthogonal directions (I_1/I_2), in the formulation of a design procedure may lead to results far from the actual ones. An example of that is illustrated by the unsatisfactory agreement between the theoretical results and those obtained from using the Direct Design Method [9]. However, at some specific beam/slab stiffness ratios the panels were found to exhibit a very particular structural behaviour, whereby the *beam load distribution were essentially uniform*. In addition to that, the *slab was in a state of no-twist with the bending*

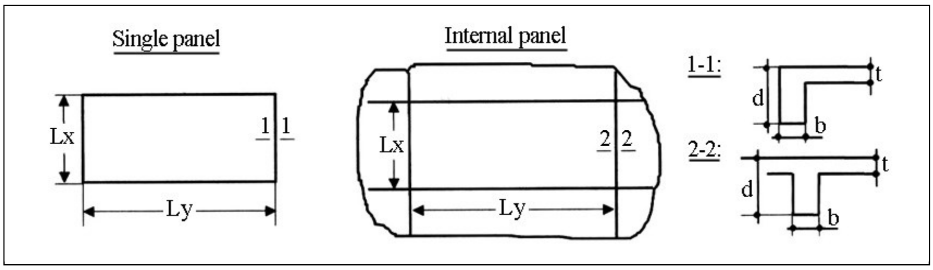

Figure 1:
Geometrical dimensions of slab-beam system.

moments uniformly distributed across the full width of the panel. These interesting cases, identified as the *elastic twistless cases*, could be exploited for developing an alternative design method for beam supported slab systems.

The present paper is mainly devoted to the determination and analysis of these elastic twistless cases, for both single and internal rectangular slab-beam systems, (Fig. 1), considering different combinations for adjacent beam stiffness (I_1/I_2) so as to cover most practical situations.

FINITE ELEMENT MODELING

The analysis was carried out by means of the finite element package PAFEC. The element used for the idealisation of the slab is a four-noded flat thin shell element which can carry both bending and membrane loads. Each node of the element has six degrees of freedom. The element used for the modeling of the beam is a simple straight beam element with offset. The element has a node, with six degrees of freedom, at each end of the shear centre, and is connected to the slab by means of offset nodes. Hence full composite action at the slab-beam junction is realised.

Tacking advantage of symmetry, only one quarter of the structure was analysed. Referring to figure 2, the symmetry conditions are modeled by restraining the following degree of freedom: θx and *Uy* (4,2) along axis *X*, and θy and *Ux* along axis *Y*. To establish the boundary conditions of a typical internal panel, zero rotation is imposed along the supporting beams as well as restraint of in-plane displacement in the direction perpendicular to the beams, as indicated in figure 2.

The results of an investigation [5] carried out to determine a suitable element mesh size show that a 12x12 mesh with a finer division at the edge is quite satisfactory.

PARAMETERS THAT INFLUENCE THE PANELS STRUCTURAL BEHAVIOUR

The structural behaviour of a slab-beam system is affected by various factors such as the supporting beams stiffness, the shape of the panel, the type of boundary, etc. Nevertheless, an attempt has been made in this study to consider the effects of most of them.

Type of boundary: the present study is concerned with cases of single and internal panels only, as illustrated in Figure 1.

Panel shape: the distribution of the elastic bending moments in a slab is very dependent upon the aspect ratio Ly/lx of the panel. In order to cover most practical situations, a range of values from 1.0 to 2.0 is considered.

Flexural stiffness parameter γ: this parameter defines the relationship between the beam and slab flexural stiffnesses, and is the controlling factor as far as the slab-beam interaction is concerned. The following table gives values of γ which are affected by both boundary conditions and direction of the panel:

Direction	Single panel	Internal panel
Long beam	$\gamma_1 = \frac{2EI_1}{DLx}$	$\gamma_1 = \frac{EI_1}{DLx}$
Short beam	$\gamma_2 = \frac{2EI_2}{DLy}$	$\gamma_2 = \frac{EI_2}{DLy}$

Where: $I_1 = \frac{b_1 d_1^3}{12}$, $I_2 = \frac{b_2 d_2^3}{12}$ and $D = \frac{Et^3}{12(1-\nu^2)}$

Adjacent beams relationship I_1/I_2: there is an unlimited number of ways in which the beam stiffnesses in the two directions could be related. One way is by expressing the ratio of their stiffnesses in terms of the aspect ratio of the panel. Thus different relations can be obtained by simply giving various degrees to this aspect ratio. It is believed that most of the practical situations can be covered by considering only the following combinations:

Relation	I_1/I_2	γ_1/γ_2
Rel (1)	$(Ly/Lx)^4$	$(Ly/Lx)^5$
Rel (2)	$(Ly/Lx)^3$	$(Ly/Lx)^4$
Rel (3)	$(Ly/Lx)^2$	$(Ly/Lx)^3$
Rel (4)	Ly/Lx	$(Ly/Lx)^2$
Rel (5)	1	Ly/Lx

	Translations			Rotations		
Degree of freedom	U_x	U_y	U_z	θ_x	θ_y	θ_z
Numerical code in PAFEC	1	2	3	4	5	6

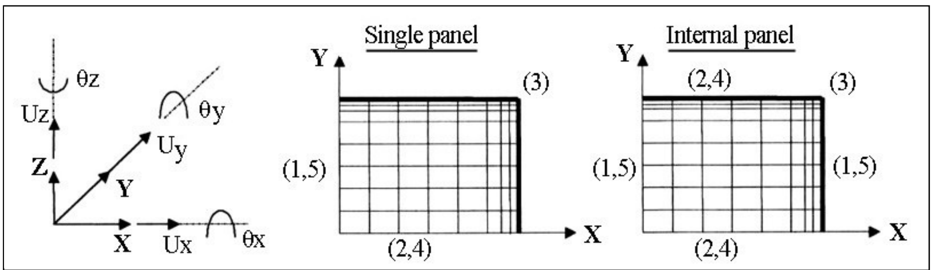

Figure 2:
Meshing and boundary constraints used in PAFEC analysis.

Ly/Lx	Parameters	Rel(1): $I_1/I_2 = (Ly/Lx)^4$		Rel(2): $I_1/I_2 = Ly/Lx)^3$		Rel(3): $I_1/I_2 =(Ly/Lx)^2$		Rel(4): $I_1/I_2 = Ly/Lx$		Rel(5): $I_1/I_2 = 1$	
		S. P.*	I. P.*	S. P.	I. P.	S. P.	I. P.	S. P.	I. P.	S. P.	I. P.
1.0	i	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	γ_1	0.50	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
	γ_2	0.50	0.55	0.50	0.55	0.50	0.55	0.50	0.55	0.50	0.50
1.2	i	0.60	0.63	0.59	0.60	0.57	0.58	0.55	0.55	0.52	0.53
	γ_1	0.82	0.85	0.76	0.77	0.72	0.69	0.66	0.66	0.59	0.58
	γ_2	0.33	0.34	0.37	0.37	0.42	0.40	0.46	0.46	0.49	0.48
1.4	i	0.69	0.72	0.66	0.68	0.63	0.64	0.59	0.60	0.54	0.55
	γ_1	1.23	1.23	1.08	1.05	0.91	0.87	0.76	0.73	0.64	0.61
	γ_2	0.23	0.23	0.28	0.27	0.33	0.32	0.39	0.37	0.46	0.43
1.6	i	0.77	0.78	0.73	0.74	0.68	0.69	0.62	0.63	0.56	0.57
	γ_1	1.73	1.67	1.41	1.32	1.09	1.07	0.85	0.81	0.69	0.67
	γ_2	0.17	0.16	0.21	0.20	0.27	0.26	0.33	0.32	0.43	0.42
1.8	i	0.82	0.83	0.77	0.78	0.72	0.73	0.65	0.66	0.57	0.59
	γ_1	2.29	2.24	1.79	1.68	1.27	1.27	0.94	0.94	0.70	0.71
	γ_2	0.12	0.12	0.17	0.16	0.22	0.22	0.29	0.29	0.39	0.39
2.0	i	0.86	0.87	0.81	0.82	0.75	0.76	0.68	0.68	0.58	0.60
	γ_1	2.90	3.02	2.10	2.10	1.44	1.47	1.02	1.02	0.73	0.74
	γ_2	0.09	0.09	0.13	0.13	0.18	0.18	0.25	0.26	0.37	0.37

Table 1: Twistless case parameters for both single and internal panels.

(*) S.P.= Single Panel
I.P.= Internal Panel

Type of loading: throughout the present study, the slab-beam systems have been taken as being subject to a symmetric transverse load applied uniformly to the slab only.

INVESTIGATION PROCEDURE

Basically the procedure for each aspect ratio consists of varying the stiffness of the supporting beams until the specific value which fulfils the following two twistless criteria is obtained:

1- Uniform distribution of the load transmitted from slab to supporting beams.

2- Equality of the parallel central and edge slab moments (*Mc=Me*).

This procedure is repeated with each of the I_1/I_2 relation defined previously. It should be noted that Poisson's ratio was assumed to be zero so as to use the second criteria which cannot be fulfilled for $\nu>0.0$. This is generally permitted by codes of practice for the analysis of concrete slab systems.

ANALYSIS OF THE RESULTS

The influence of the ratio I_1/I_2 is clearly illustrated by the results in figures 3, 4 and 5, which indicate that the slab-beam system, either single or continuous, undergoes a complete reversal of structural behaviour from Rel(1) to Rel(5). Most of the analysis below is concerned with Rel(1) and Rel(5) because they represent the limits of all relations considered.

Twistless γ values:

As expected, for each relation I_1/I_2 there corresponds a specific set of γ_1-γ_2 values which vary with the panel shape. It is of interest to note, as illustrated in Table 1, the closeness of γ_1-γ_2 values obtained for both single and internal cases. An examination of the curves plotted in figure 6 reveals that from Rel(1) to Rel(5), the twistless behaviour of the structure is achieved with long beams decreasing in stiffness and short beams increasing in stiffness.

Load distribution, bending moments and deflections:

When reference to support conditions is disregarded, the only controlling factor concerning the load distribution is the panel aspect ratio *Ly/Lx*. But when the stiffness of the porting beams is taken into account, the relation I_1/I_2 may have a significant influence on the way in which the load is carried to the supports, as shown in Figures 3, 4 and 5.

As far as Rel(1) is concerned, the load is found to be increasingly carried in the short direction as the panel gets longer. As a result the bending moment of the short span and the long beam are significantly increased, indicating thereby the trend of the structure towards one-way spanning behaviour. Thus for *Ly/Lx*=2.0, the load transmitted to the long beams represents approximately 85% of the total load. Unlike Rel(1), in the case of Rel(5) an important part of the load is still carried in the long direction despite an increasing aspect ratio. Hence, in this situation the long slab span as well as the short beam become more structurally involved as expressed by the continuous increase of their respective bending moments. Thus for *Ly/Lx*=2.0, about 40% of the total load is delivered to the short beams. It is interesting to note here, that a slab-beam system which complies with Rel(5) features remains in a state of two-way spanning action even though *Ly/Lx*=2.0.

The analysis of figures 3, 4 and 5 indicates that from Rel(1) to Rel(5) the same panel undergoes several phases in the load transmission to supports, which may be described as follows: as the ratio I_1/I_2 gets smaller a part of the load carried in the short direction is transferred in the long direction. In this respect, the designer is given some *freedom* of choice regarding the way he wishes the load to

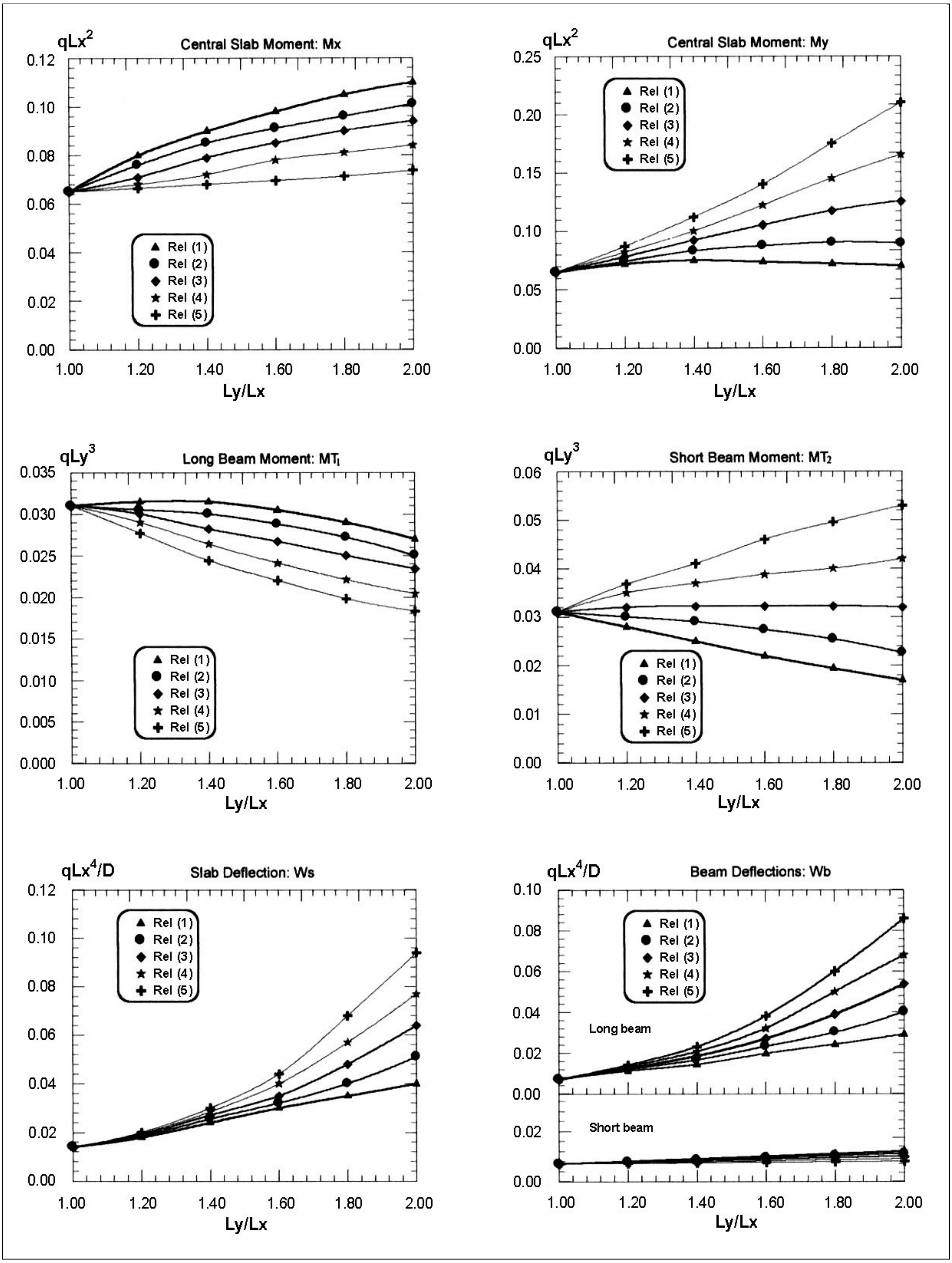

Figure 3: Effects of the panel shape and the ratio I_1/I_2 on the twistless behaviour of a single slab-beam system.

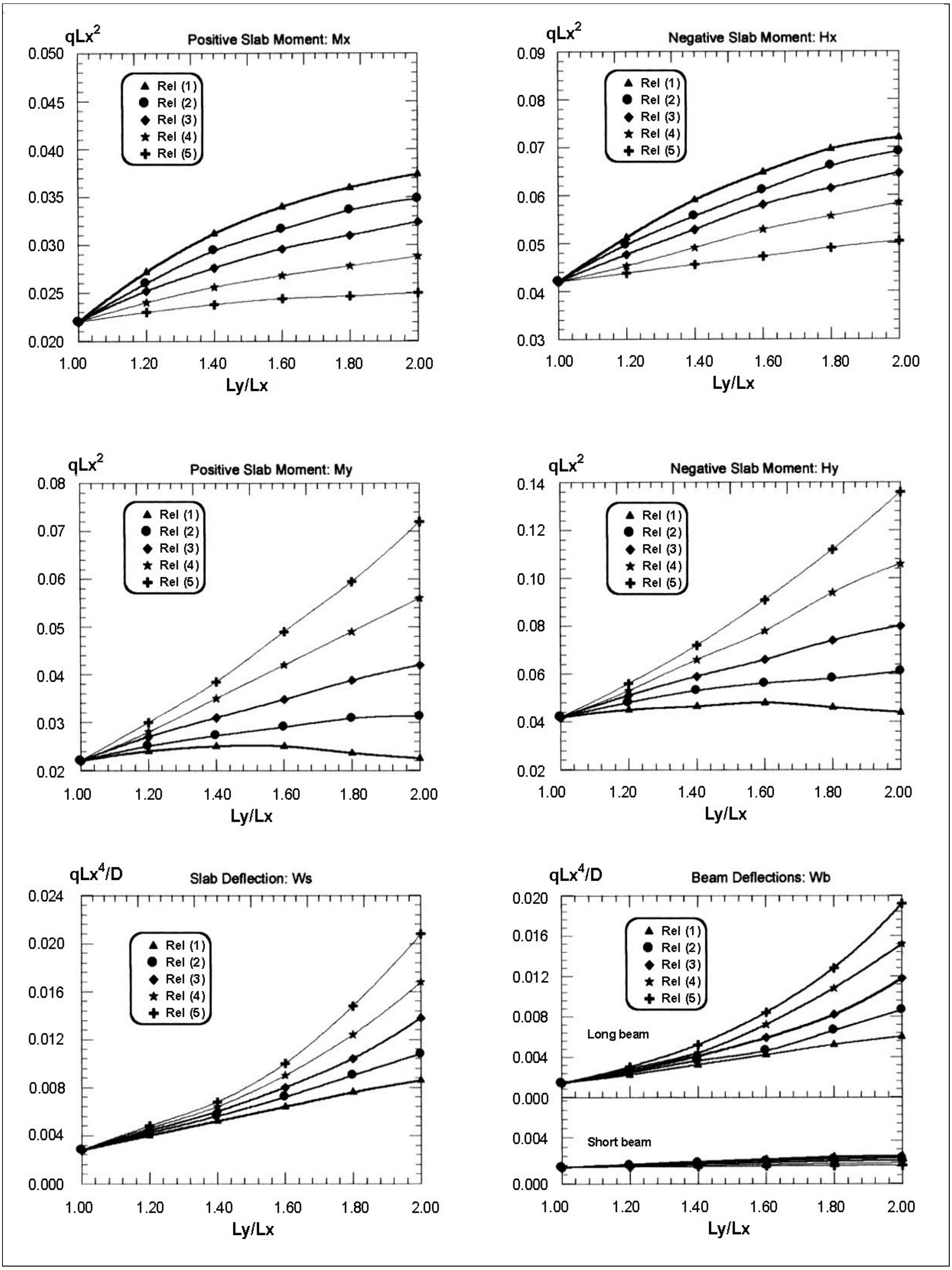

Figure 4: Effects of the panel shape and the ratio I_1/I_2 on the twistless behaviour of a internal slab-beam system.

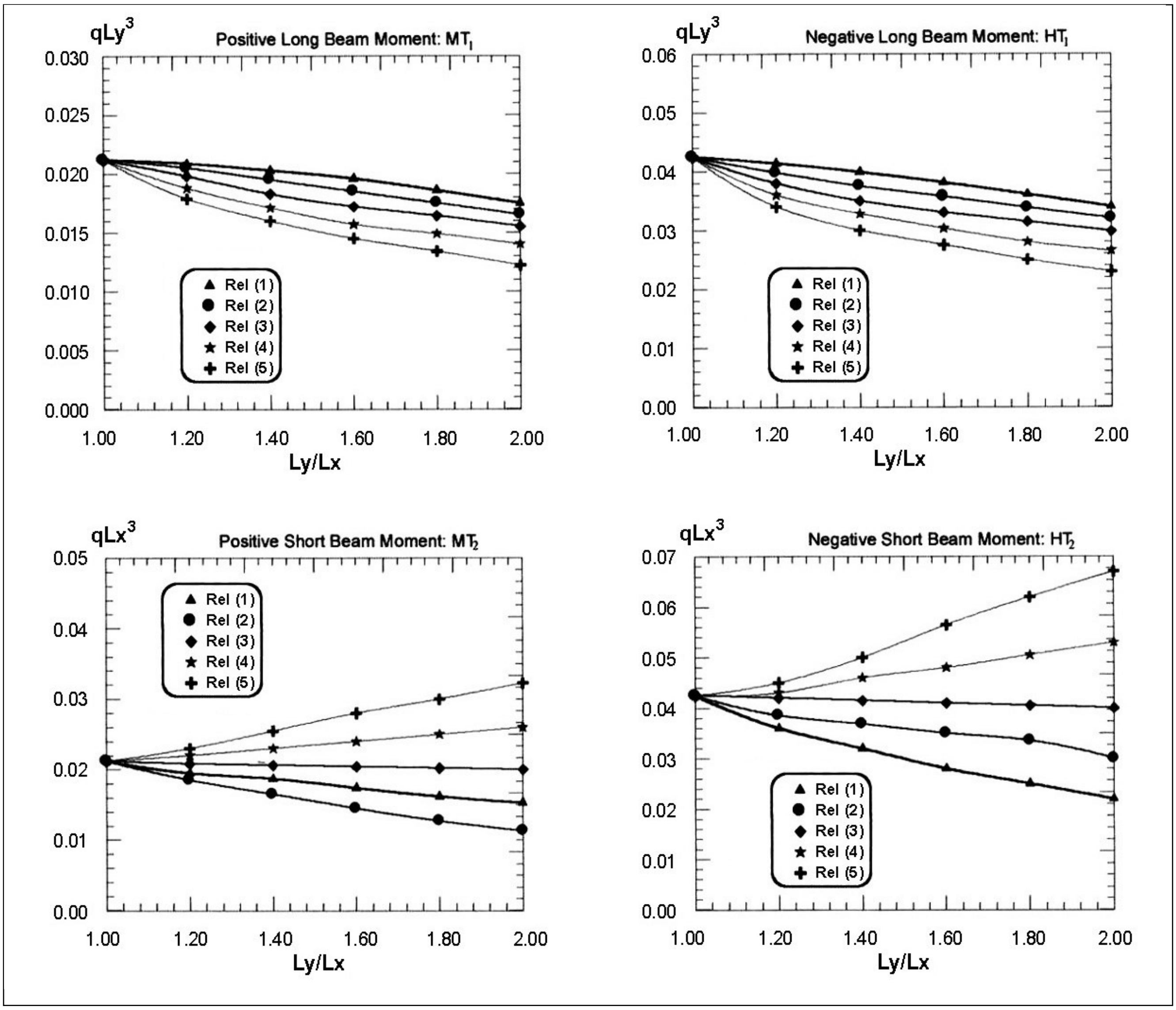

Figure 5: Effects of the panel shape and the ratio I_1/I_2 on the twistless behaviour of a internal slab-beam system.

be transmitted to the supporting beams, provided the appropriate I_1/I_2 is adopted.

The influence of the beam stiffness relationship on the slab and beam deflections is clearly shown in Figures 3, 4 and 5. Higher values of I_1/I_2 lead to lower deflections for long beam and slab, but increase slightly short beam deflections. Therefore, the serviceability of the structure is very dependant on the choice of I_1/I_2 ratio which would have to be made with some care.

SIMPLE EXPRESSIONS FOR ELASTIC TWISTLESS CASES

For the case of slab-beam systems with partial composite action only, i.e. the slab and beam neutral axis are at the same level, it was found that when the product $\gamma_1 \gamma_2$=1.0, twistless action occurs [1]. A similar expression can be determined from considering the trend of variation of γ_1-γ_2 with the ratio I_1/I_2 and the panel shape Ly/Lx shown in Table 1. The best expression found for the condition governing twistless behaviour in fully composite slab-beam systems is:

$$\gamma_1 = \gamma_2 = 0.28 \tag{1}$$

A comparison of the results produced by this simple equation with those in Table 1 indicates a maximum difference of 12%. Regarding the load distribution factor *i*, the following expression was found to give results with a maximum 4% variation from those in Table 1:

$$i = \frac{\left(\gamma_1 / \gamma_2\right)^{0.5}}{1 + \left(\gamma_1 / \gamma_2\right)^{0.5}} \tag{2}$$

Thus the twistless parameters of a slab-beam system with any I_1/I_2 ratio, even outside the range of ratios considered, can be determined with a good approximation from using Equations 1 and 2.

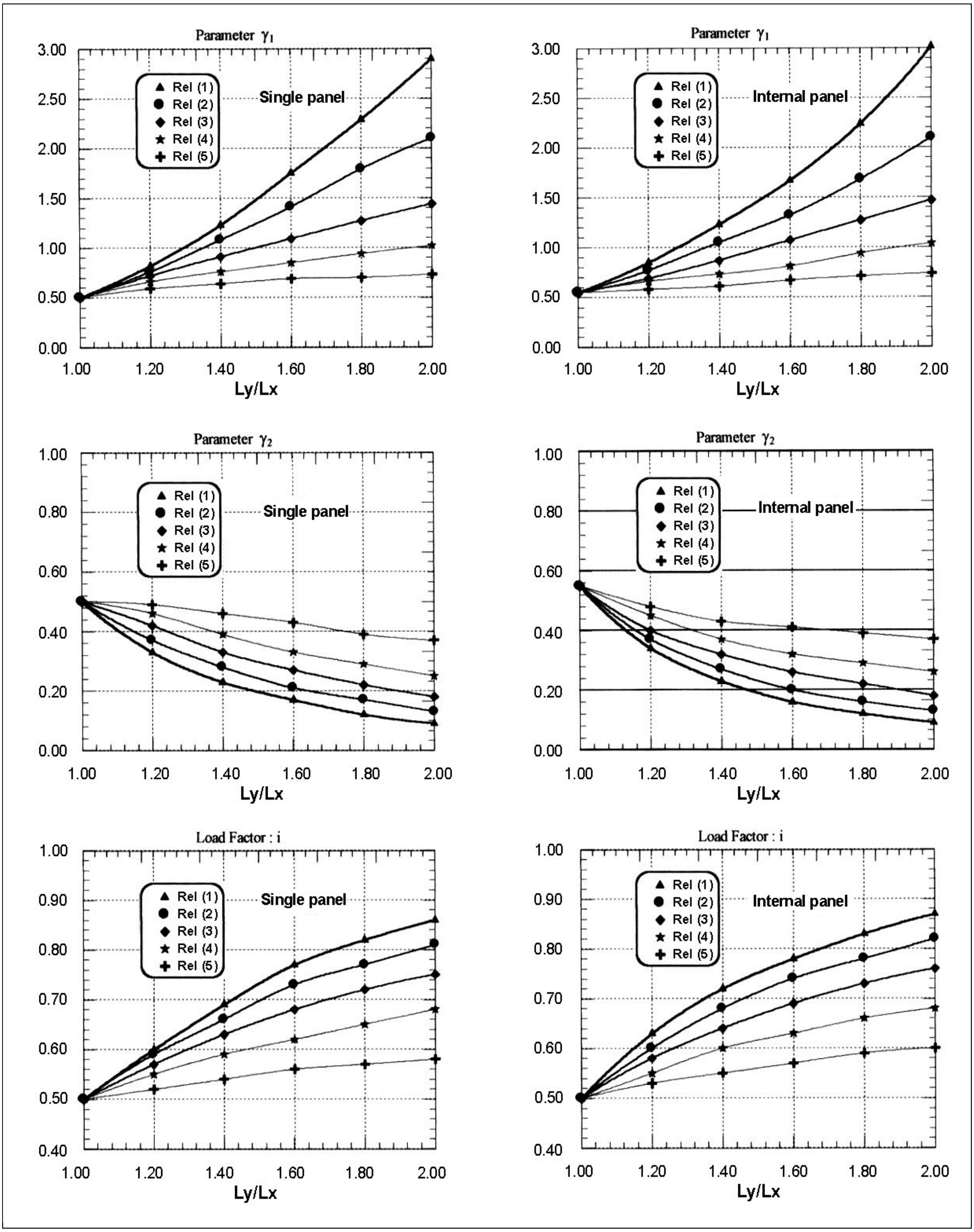

Figure 6: Beam/slab stiffness ratios and load distribution factors for twistless behaviour in slab-beam systems.

EXPERIMENTAL INVESTIGATION

In order to verify the accuracy of the analytical results, obtained for the elastic twistless cases, tests have been performed on small scale models which consisted of a series of single slab-beam panels with different aspect ratios. Each model has been given the relevant beam/slab stiffness ratios, considering the case of Rel(5), so as to simulate an elastic twistless behaviour under the action of a uniform load.

Description:

The models were made from a material called Tufnol which is a laminated plastic material based on phenolic resin with medium weave fabric reinforcement. It was preferred to Perspex because it has a relatively lower Poisson's ratio and exhibits less creep under stress in the elastic range though its modulus value is relatively high.

The construction of the test models was carried out from sheets 12.7mm thick, and the width of the plates was worked out on the basis that Lx/t=40. The dimensions of the beams sections were derived from values of γ_1-γ_2 corresponding to Rel(5) twistless cases. The edge beams were bonded to the plates with Epoxy cement and were kept under pressure by means of clamps for at least 24 hours. The bond strength of a cemented double lap joint specimen tested in shear two days after assembly reached a value of not less than 4.5N/mm^2. Since the mating surfaces were expected to be subjected to smaller stresses as they are close to the neutral surface of the composite beams, it was concluded that good monolithic joints exist between the slab and its supports.

At each of the beam supports the corner moments and the lateral restraint were made zero by supporting the beam ends on a steel ball bearing which sits in a V-groove of a (30x3x5mm) steel plate attached to rigid boxes. Thus a each corner of the model is provided one lateral degree of freedom the direction of which is shown in Figure 7.

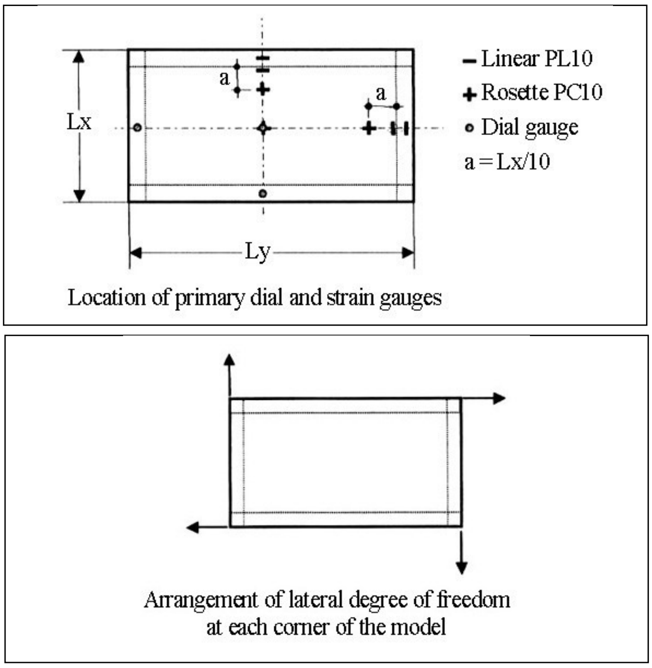

Figure 7: Single slab-beam model.

Due to the relatively high modus of Tufnal material, the use of dead weights as a method of loading may require a significant quantity of weights in order to obtain satisfactory strain readings. Alternatively, the system adopted was that of loading through a hydraulic machine, which provides a single load. This latter was divided into eight single loads through the system shown in Figure 8. Each of these eight loads was applied to a 50mm thick concrete panel resting on a thick rubber pad. In this way, the initial load was believed to have been quite fairly distributed over the slab.

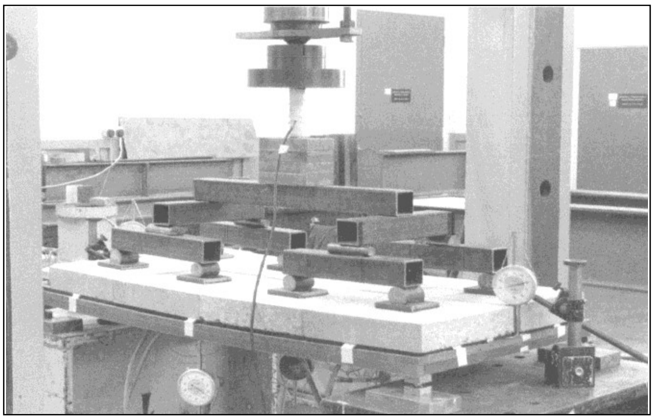

Figure 8 : General test setup.

The measurement of the surface strains of the models were carried out using both one-way 10mm PL10 and two-way 10mm PC10 electrical resistance strain gages. Their locations on the models are defined in Figure 7. In addition to these primary gauges, a few random gauges were positioned at points where strains were expected to be similar on account of symmetry. These served as control gages to enable any possible deviation from symmetry during test to be detected. At all locations, strain gauges were fixed to both top and bottom surfaces of the model. Vertical deflections were measured by means of dial gages with a resolution of 0.01mm. The location of these dial gages is indicated in Figure 7. Some of them were used to check that the behaviour of the model was symmetrical.

The various aspects of the experimental investigation regarding the determination of model material properties, the sequences of the test procedure, the evaluation of test results are fully described in reference [5].

EXPERIMENTAL VERSUS THEORETICAL RESULTS

The slab-beam models tested were also analysed by PAFEC, with Tufnal properties E=7250 N/mm^2 and ν=0.27, so as to enable a comparison with the experimental results. In this respect, it must be appreciated that the degree of correspondence, between theoretical and experimental results, is influenced by inaccuracies, which are present in both sets of results [10]. Examination of Figure 9 indicates that the pattern of variations of the theoretical results is reasonably well reflected in the experimental results.

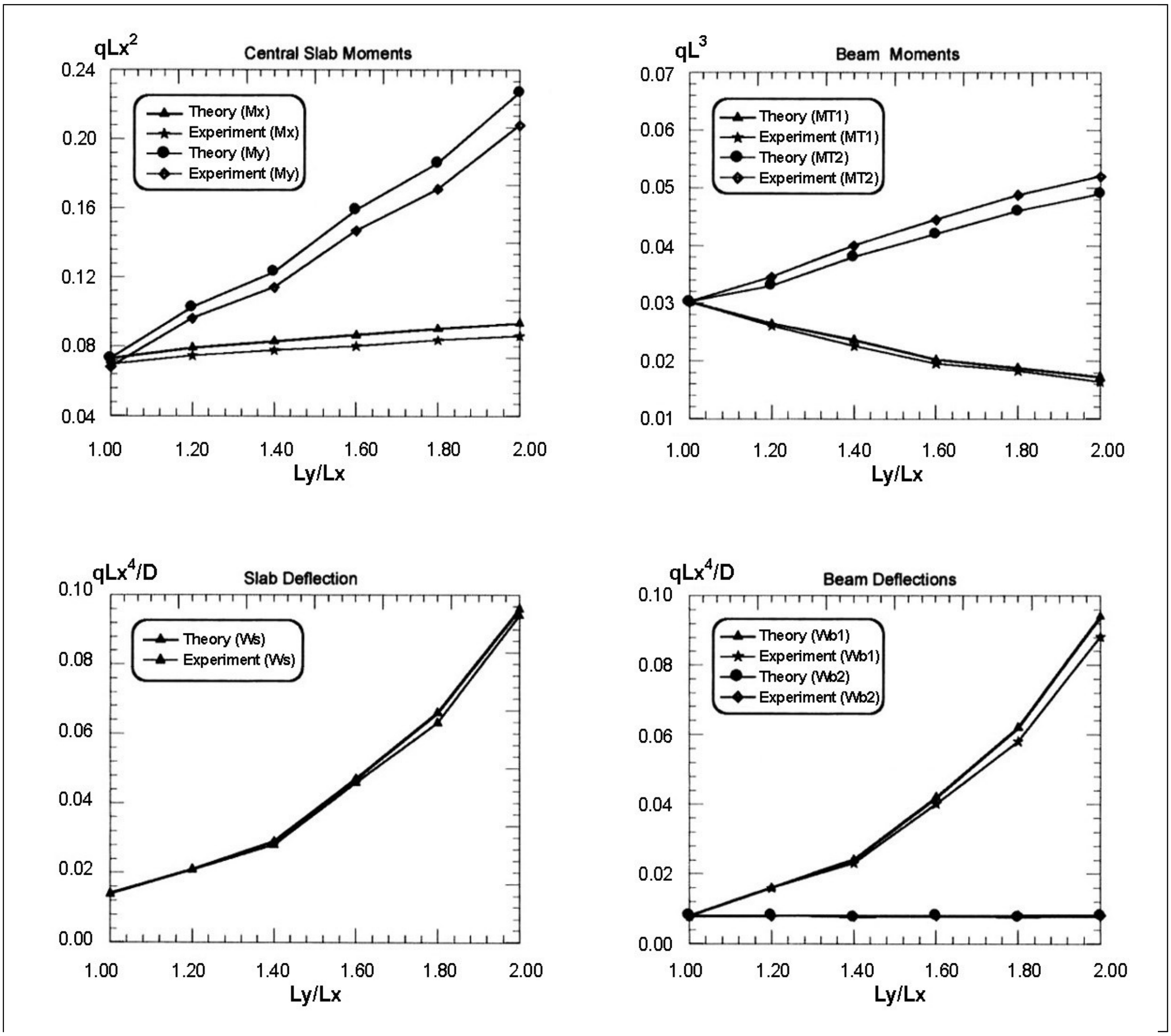

Figure 9: Theoretical and experimental results of a single slab-beam system with various panel shapes.

***Slab bending moments*:** the test results display a satisfactory agreement with theory; the maximum variation between the curves is 10% for all the panel shapes considered. The results given in Table 2 also indicate a good correspondence between theory and tests with respect to distribution of moments across the centre lines of the slab. And since the results obtained from PAFEC showed that the load distribution on the beams is fairly uniform, it may be concluded that the structural behaviour of Tufnol models is close to that of twistless case.

Beam bending moments: the agreement is generally acceptable (within 15%), with the theoretical results lower than the test results regarding the short beams. This was due to the part of moment carried by L-beam action which was found to be higher than that given by theory [5]. However, the situation is reversed with the long beams.

Deflections: their theoretical and experimental curves are plotted in figure 9 which shows a reasonably good correlation between them and their consistency with the bending moment results. A comparison of the corresponding slab and beam deflections indicated a maximum variation of 20% for all the panel shapes considered.

USEFULNESS OF THE TWISTLESS CASES FOR DESIGN

The formulation of a design procedure on the basis of twistless moment field is similar to the approach undertaken by Hillerborg in developing his Simple Strip Method [11]. The latter is one of the design methods for reinforced concrete slabs recommended by some codes of practice. Hillerborg considered the equilibrium equation for an element of slab:

$$\frac{\partial^2 Mx}{\partial x^2} + 2\frac{\partial^2 Mxy}{\partial xy} + \frac{\partial^2 My}{\partial y^2} = -q \qquad (3)$$

Ly/Lx	Source	Across long span			Across short span		
		centre	Lx/10	edge	centre	Lx/10	edge
1.0	Theory	0.0730	0.0658	0.0614	0.0730	0.0658	0.0614
	Experiment	0.0695	0.0638	0.0605	0.0680	0.0626	0.0600
1.2	Theory	0.0792	0.0702	0.0651	0.1025	0.0952	0.0915
	Experiment	0.0744	0.0680	0.0638	0.0961	0.0912	0.0896
1.6	Theory	0.0867	0.0752	0.0694	0.1590	0.1510	0.1470
	Experiment	0.0802	0.0724	0.0675	0.1470	0.1415	0.1390
2.0	Theory	0.0935	0.0790	0.0723	0.2270	0.2170	0.2150
	Experiment	0.0862	0.0760	0.0710	0.2080	0.2010	0.1990
Multiplier		qLx^2					

Table 2 : Theoretical and experimental slab moment distribution across centre lines of the model shown in Figure 7.

According to the lower bound theory, any combination of *Mx*, *My* and *Mxy* moments which satisfies Equation 3 at all points in the slab and the boundary conditions, when the ultimate load is applied, is a valid design solution provided that reinforcement is placed to carry these moments. Hillerborg's approach is to deliberately eliminate the contribution of the twisting stiffness to the load carrying capacity of the slab by making Mxy=0 at all points. Thus, it is easy to choose the distribution of the intensity of loading q in two orthogonal directions so that: $qx=iq$ and $qy=(1-i)q$. The plate continuum problem is thereby reduced to the analysis of beam strips where,

$$\frac{\partial^2 Mx}{\partial x^2} = -iq \quad \text{and} \quad \frac{\partial^2 My}{\partial y^2} = -(1-i)q \qquad (4)$$

The method is computationally simple, provides full information on the moment field, and leads usually to a unique load solution. Unfortunately, it does have serious shortcoming:

1- The designer may choose load distribution which depart far from working load conditions, which could lead to a slab which, although satisfying strength requirements, may be unserviceable due to wide cracking or excessive deflections at service load.

2- No consideration is given to the stiffness of the supporting beams for the case of slab-beam system.

As an alternative, a direct design procedure for beams supported slab, free from the disadvantages listed above, could be developed on the basis of twistless elastic solutions. These latter are not just assumed as for the Simple Strip Method but rather built up from a geometrical relationship governing the combined behaviour of the system. This matter will be dealt with in a separate paper.

CONCLUSION

Both internal and single slab-beam panels, subject to a uniformly distributed load, have been examined. The analysis has been carried out using a finite element package PAFEC considering various aspect ratios and various adjacent beam stiffness relationships (I_1/I_2). The object has been to determine values of γ_1-γ_2 for which the distribution of the bending moments across the slabs in the two orthogonal directions is uniform, as is the load distribution on the supporting beams. These twistless cases provide an interesting basis for developing an alternative design procedure for slab-beam systems. An experimental investigation has been carried out on a series of single slab-beam models in order to check the accuracy of these theoretical results. By examining these elastic twistless cases results, it may be concluded that:

- The character of the combination relating I_1 and I_2 is of great importance insofar as the structural response of the panel is concerned. Considering Rel(1), twistless action occurs with relatively rigid beams in both directions because of their identical span-to-depth ratios. Therefore it is the aspect ratio *Ly*/*Lx*, which becomes the controlling factor of the structural behaviour of the system, i.e. as the panel gets longer it tends to behave like a one-way slab. Whereas in the case of Rel(5) the system remains spanning in the two directions even for *Ly*/*Lx*=2.0, because of the comparatively higher rigidity of the short beams. It is important to realise here that such a variety of behaviour benefits the designer, as it gives significant freedom on how to split up the total load in the two orthogonal directions by adopting the appropriate I_1/I_2 relation.
- The results obtained show that it is possible to have a combination of strong beams in one direction and weak beams in the other direction and yet obtain twistless behaviour.
- The geometrical dimensions required for the system in order to bring about elastic twistless behaviour are for most cases practical, particularly with lower slab *Lx*/*t* ratios.
- Although the slab and beam deflections are primarily dependant on the ratio *Lx*/*t*, the influence of the I_1/I_2 relation is by no means negligible. Hence the choice of I_1/I_2 ratio should be made such that satisfactory serviceability in the slab-beam system is achieved.
- A good agreement was observed between the test results obtained from the various single models and those predicted by theory, particularly the results of the distribution of the slab moments across the panels. On the whole, the experimental investigation provides sufficient evidence to support the validity of the theoretical twistless cases.

NOTATIONS

d	Depth of beam.
b	Width of beam.
t	Thickness of beam.
Ly	Long span.
Lx	Short span.
Ly/Lx	Aspect ratio.
Lx/t	Slab span-to-depth ratio.
q	Intensity of loading on slab.
E	Young's modulus of elasticity.

ν	Poisson's ratio.
I	Second moment of area of beam about horizontal centroid axis.
D	Flexural stiffness of slab per unit width.
γ	Ratio of flexural stiffness of beam to slab
W	Deflection.
Mx, Hx	Positive and negative moments per unit width of slab in direction of span Lx.
My, Hy	Positive and negative moments per unit width of slab in direction of span Ly.
Mxy	Twisting moment in slab.
MT, HT	Positive and negative moments in equivalent (L or T) beam.
i	Distribution load factor for the short span.

SUFFIXES

b	Denotes beam
c	Denotes centre of slab
e	Denotes edge of slab
s	Denotes slab
1	Denotes long beam
2	Denotes short beam

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