CHAPTER 5

DESIGN APPROACH

5.1 Design Criteria

Structural design of link slabs must be able to ensure its strengths in worst cases for structural safety, and to satisfy its serviceability under normal working conditions avoiding detraction from appearance, durability or performance of the structure. The link slab must be able to accommodate all end movements of adjacent girders as the restraints including moving loads on link slabs which can be converted to axial force, moment and shear.

The end movements of simply supported girders which are axial deformation and end rotation due to long-term effects (creep, shrinkage and steel relaxation) and short-term effects (live load, temperature gradient and ambient temperature) are determined. The important variables related to these end movements are section property and span length.

The interaction model on link slab restraints is related to adjacent girders, link slabs and support conditions including the position of link slabs on the overall jointless structure. The designed elastomeric bearing at each position is related to the number of spans on a jointless structure because of the maximum reversible longitudinal movement of girders at each position, the minimum vertical load and the maximum vertical load per one elastomeric bearing. From the chosen elastomeric bearings at each position, the vertical and horizontal stiffness of elastomeric bearing can be calculated.

From the free end movements which are axial deformation and end rotation, the axial and rotational restraints in link slabs can be determined by the relative stiffness of composite girders and link slabs including the position of link slabs and can be converted to axial force and bending moment varied with effective stiffness of link slab. From the link slab stiffness and the existing vertical stiffness of elastomeric bearings which are different from the position of the link slab, the translational restraint can be determined in terms of moment and shear in the link slab. From the horizontal stiffness of elastomeric bearings and the position of each bearing, the axial force in link slabs can also be determined.

In summary, the criteria for design of link slab would require end restraints and traffic loading which are interacted to obtain internal forces, strain gradient as well as cracks and deformations. The concept for the design then would be compliance with the strength of the ultimate limit states and satisfied with the serviceability of the serviceability limit states.

5.2 Design Approach

Since the internal forces, strain gradients, cracks and deformations of link slabs depend on actions and three primary variables of girder details, thickness-to-span length ratio of the link slabs and the condition of supports as per its position in the structural system (stiffness of elastomeric bearings), then design approach (as shown in Fig. 5.1) of the link slab would consider the following approaches:

1. Each span of the jointless bridge deck can be designed as a simply-supported girder using the standard design procedures. The effect of continuity due to the link slab is negligible because the stiffness of the link slab is much smaller when compared to that of the girders. The end movements of simply supported girders which are axial deformation and end rotation due to long-term effects (creep, shrinkage and steel relaxation) and short-term effects (live load, temperature gradient and ambient temperature) are determined to be the most extreme cases and actions of link slab of the structural system. From 4 favorable cases of end movements, the maximum shortening case and maximum downward end rotation case are used to form a movement combination.
2. The preliminary thickness and span length of link slabs can be determined. The flexural stiffness of the link slab can be tentatively determined with its dimensions with regard to the end rotation of girders. The relative stiffness between composite girders and link slabs can be assumed and the interaction model among the actions of end movements can be set to determine the end restraints of link slabs which are axial and rotational restraints. Bending moment due to rotational restraint and axial force due to axial restraint can be found by the product of end restraints and link slab stiffness. Rotational restraint is dominant in comparison with axial restraint. Moment is changed by

link slab stiffness and rotational restraint so the rotational restraint-moment chart (Fig. 5.2) can be used as a tool to find out.

3. The support conditions would be related to the structural systems with the number of continuous jointless spans with link slabs and its position. The elastomeric bearing pad is designed for allowable movements at each position due to elongation along the route. The additional axial force in link slabs due to elastomeric bearing deformation is determined by summation of elastomeric friction forces through the free end. The additional moment and shear from translational restraint (end translation and moving load) due to differential settlement of elastomeric bearings are also the actions of link slabs. The moment due to wheel load varied with the detailing of reinforcement in link slab is also determined. The internal forces of link slabs which are flexure, axial and shear forces are analyzed and designed for reinforcement.
4. To design for strength of link slab, the maximum axial force must be controlled by tensile reinforcement as which the bending moments at mid-span and both ends shall be controlled by coupling of compression of concrete and the tensile of the reinforcing steel to encounter the resisting moment. Shear which is subjected to the moving loads is designed for concrete resistance.
5. To design for serviceability, crack control by means of tensile reinforcement with regard to specific details. Support conditions as per its position in the structural system and the stiffness of elastomeric bearing pad can be adjusted to proper manner in operation and maintenance. Finally, the crack width and crack distribution can be controlled by a larger size bar, reducing the bar spacing and reinforcement detailing. If the crack width can not be controlled, it is forced by reinforcement detail to happen at one position to be easily maintained.
6. If the axial force in link slabs at mid-route of a jointless highway, where the maximum axial force is taken, is more than cracking force, the number of spans on the jointless highway can be repeatedly chosen and the horizontal stiffness of elastomeric can be adjusted to be more flexible. If the shear capacity is not enough, the vertical stiffness of elastomeric bearings can be adjusted to be stiffer or the link slab dimension can be changed. If the flexural capacity of the link slab section is not enough, its dimensions and the vertical stiffness of elastomeric bearing can be adjusted.

5.3 Design Example

To illustrate the above design procedure for the link slabs, the elevated highway with simply supported highway girders and link slabs has been designed.

Step 1. Determination of precast girder end movments

I-section is chosen to be a typical girder with a 30 meter span length, 2.67 meter spacing, with 20 cm cast in-situ deck. The flexural stiffness (*I/L*) of the composite section per one girder is 0.01507 m^3. The temperature gradient and ambient temperature is about 25 $^{\circ}C$ in Thailand. The axial deformation and end rotation of maximum shortening and elongation cases are 11.33 mm (shortening), 4.13×10^{-4} rad (upward) and 7.74 mm (elongation), 3.90×10^{-3} rad (downward) respectively. In addition, the axial deformation and end rotation of maximum upward and downward end rotation cases are 5.31 mm (shortening), 8.62×10^{-4} rad (upward) and 1.71 mm (elongation), 4.35×10^{-3} rad (downward) respectively.

Step 2. Choice of link slab dimensioning

The link slab thickness and span length are chosen from the adjacent deck thickness and possible span length. Preliminary design for this case is 20 cm thickness and 2 m span length so the flexural stiffness (*I/L*) of link slabs is 0.00042 m^3 for the uncracked section.

Step 3. Choice of the structural systems as the number of girder spans and the support condition

For 30 meter span length of simply supported girders, the maximum reversible longitudinal movement per 1 span is about 8 mm, the minimum vertical load (dead load only) is about 80 T per 1 girder and the maximum vertical load (including live load) is about 120 T. The elastomeric bearing pad at each position and number of spans can be chosen from the maximum reversible longitudinal movement, the minimum vertical load and maximum vertical load per one elastomeric bearing. The 6-span of simply supported girders is chosen to be constructed with link slabs, so the maximum longitudinal movement is about 0.3 mm, 8.5 mm, 9 mm, 17 mm, 18 mm, 26 mm at the 1st to 6th positions of support from mid-route respectively. The minimum and maximum vertical load per one bearing is about 40 and 60 T.

From the chosen elastomeric bearings at each position, the vertical and horizontal stiffness of elastomeric bearing can be calculated. The horizontal stiffness of elastomeric bearing is $3.31\text{x}10^2$, $1.81\text{x}10^2$, $1.25\text{x}10^2$ and $1.03\text{x}10^2$ kg/mm at 1st, 2nd - 3rd, 4th - 5th and 6th positions respectively. The vertical stiffness of elastomeric bearing is $1.34\text{x}10^5$, $6.94\text{x}10^4$, $4.68\text{x}10^4$ and $3.84\text{x}10^4$ kg/mm at 1st, 2nd - 3rd, 4th - 5th and 6th positions respectively.

Step 4. Forces in link slab

a) Axial force in link slab

The axial force that is produced in link slabs can be calculated by summation of products of horizontal stiffness and longitudinal movement at each position to the free end. So they are approximately 10.3, 8.7, 4.9 T at 1st, 2nd - 3rd, 4th - 5th positions of link slabs along the route. The maximum axial force of link slabs occurs at the 1st position or at the mid-route of the jointless highway which is about 2 kg/cm^2 that is less than cracking stress of concrete. So the number of spans is suitably chosen.

b) Shear force in link slab

The critical shear force occurs at the minimum vertical stiffness of elastomeric bearing which is at the 4th - 5th positions in this case. The relative stiffness (α ,$Kv/[12EI/L^3]_{\text{link slab}}$) is about 14.1 which is in the boundary of the proposed relative stiffness for shear force, so the shear force at the edge of link slabs is less than the moving load (P). It can be calculated by Eqs.(3.13-3.14) so the calculated shear force is 3.34 T and 8.28 T at end and mid-span of link slab.

c) Flexure in link slab

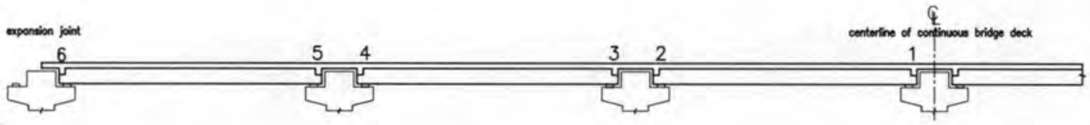
The critical flexure due to end translation and moving load occurs at the minimum vertical stiffness of elastomeric bearing where is at 4th - 5th position in this case. The relative stiffness (α , $Kv/[12EI/L^3]_{\text{link slab}}$) is about 14.1 which is not in the boundary of the proposed relative stiffness, so the additional flexure that occurs in link slabs is more than $PL/8$. The additional flexure can be calculated by Eqs.(3.11-3.12) so the additional flexure is 4.78 T-m and 2.86 T-m at end and mid-span of link slab.

The rotational restraints can be calculated by using the interaction model and end movements of simply supported girders. The relative stiffness ($(EI/L)_{composite\ girder}/(EI/L)_{link\ slab}$) is about 40 to 120 depending on cracking in link slab. The calculated end restraint followed Fig. 3.30 is about $4.35\text{x}10^{-3}$ rad or 0.002 rad/m. The flexure due to rotational restraint can be easily followed by Fig. 5.2 which is about 3 – 5 T-m/m or 8.0 – 13.4 T-m.

The maximum bending moment at the mid-span is due to rotational restraint and mid-span loading, and the one at both ends of link slab is due to rotational restraint and translational restraint. So the designed bending moments at end and mid-span of link slab are about 18.17 and 16.26 T-m respectively.

Step 5. Dimensioning for strength and serviceability

The axial force in link slabs is less than the cracking force so the reinforcement strain due to axial force is also less than strain due to bending moment. Using the same amount of reinforcement at top and bottom of link slab, the tensile reinforcement is yield but the compression reinforcement is not yield under the bending moment. So the section capacity and ultimate moment can be determined. From the moment in link slab, the reinforcement is designed to control the crack width by limited reinforcement strain and ultimate moment. DB16@75 is designed for reinforcement and the strain is limited by 40% of yield strain. Ultimate moment is about 33.6 T-m. And the shear capacity of the section (*Vc*) is 36.77 T which is less than factored shear force.



Maximum longitudinal movement due to ambient temperature, mm						
	26	18	17	9	8.5	0.3
Horizontal stiffness of elastomeric bearing (K_H), x10^2 kg/mm						
	1.03	1.25	1.25	1.81	1.81	3.31
Vertical stiffness of elastomeric bearing (K_V), x10^4 kg/mm						
	3.84	4.68	4.68	6.94	6.94	13.4
Axial force in link slab due to elastomeric bearing deformation (T)						
		4.9		8.7		10.3
Shear force in link slab due to elastomeric bearing settlement (T)						
V_{max} at end-section		3.34		2.73		1.03
V_{max} at mid-section		8.28		8.28		8.28
Bending moment in link slab due to elastomeric bearing settlement (T-m)						
M_{max} at end-section		4.77		4.63		4.52
M_{max} at mid-section		2.86		2.86		2.86
Bending moment in link slab due to girder movments (T-m)						
M_{max}		13.4		13.4		13.4
Designed force of link slab						
Axial force (T)		4.9		8.7		10.3
Shear force (T)		8.28		8.28		8.28
Bending moment (T-m)		18.17		18.03		17.92

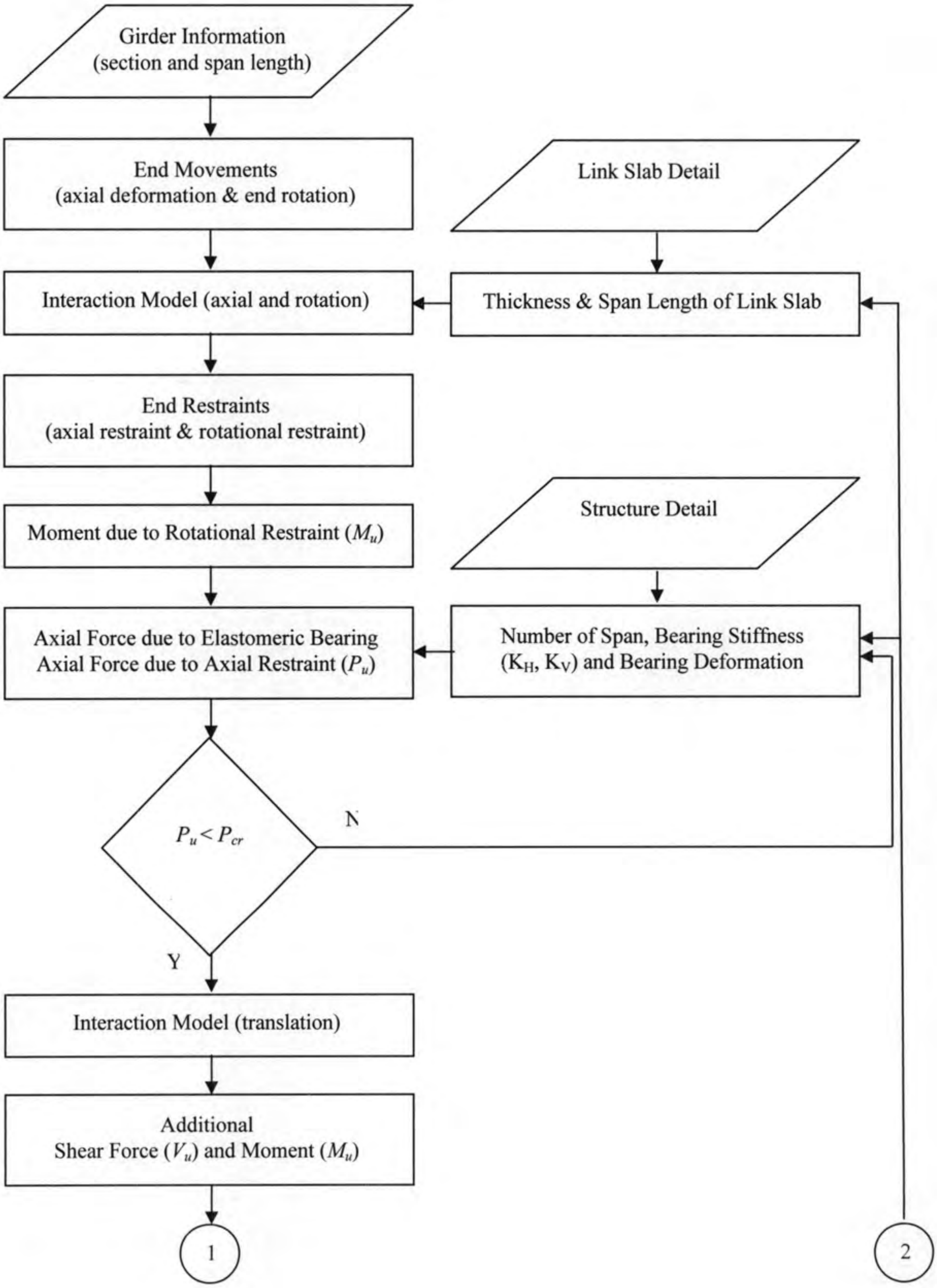


Fig. 5.1 Design approach

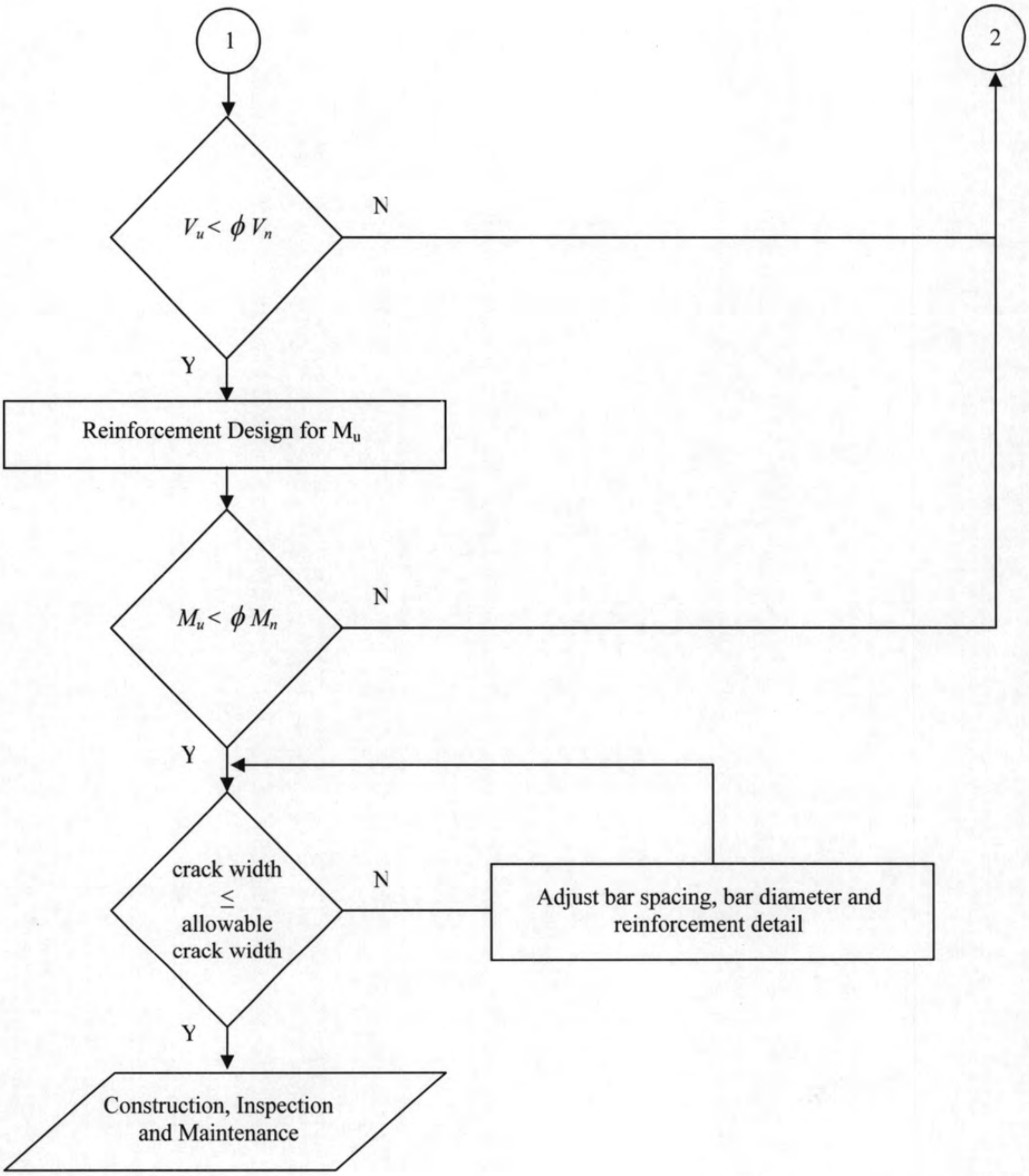
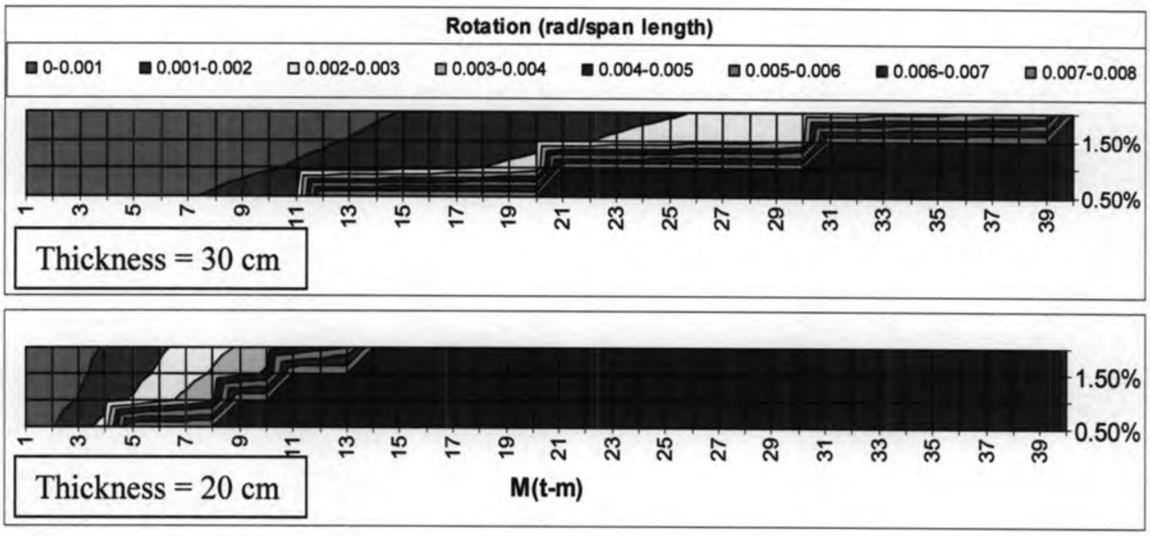
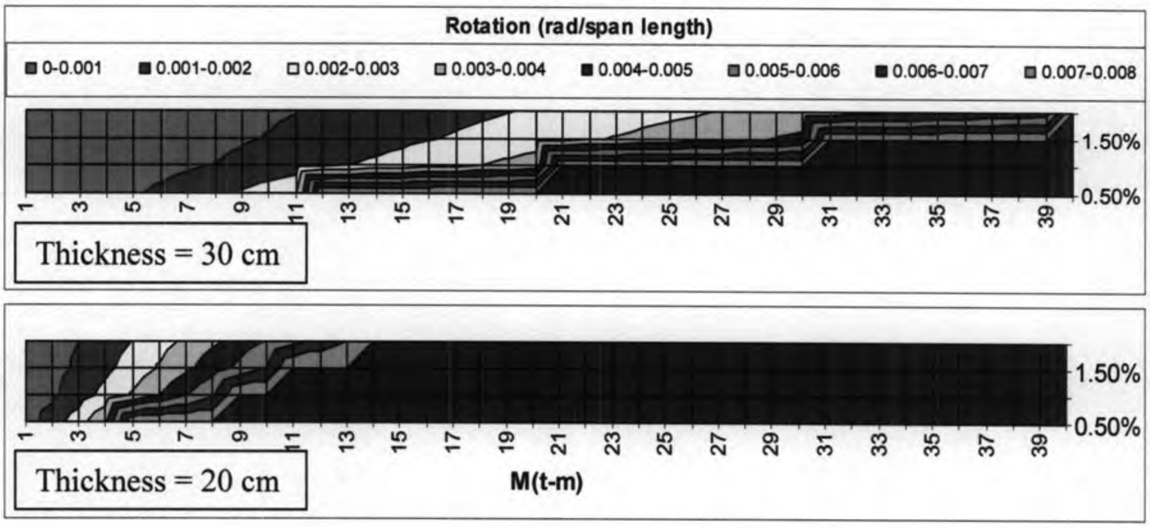


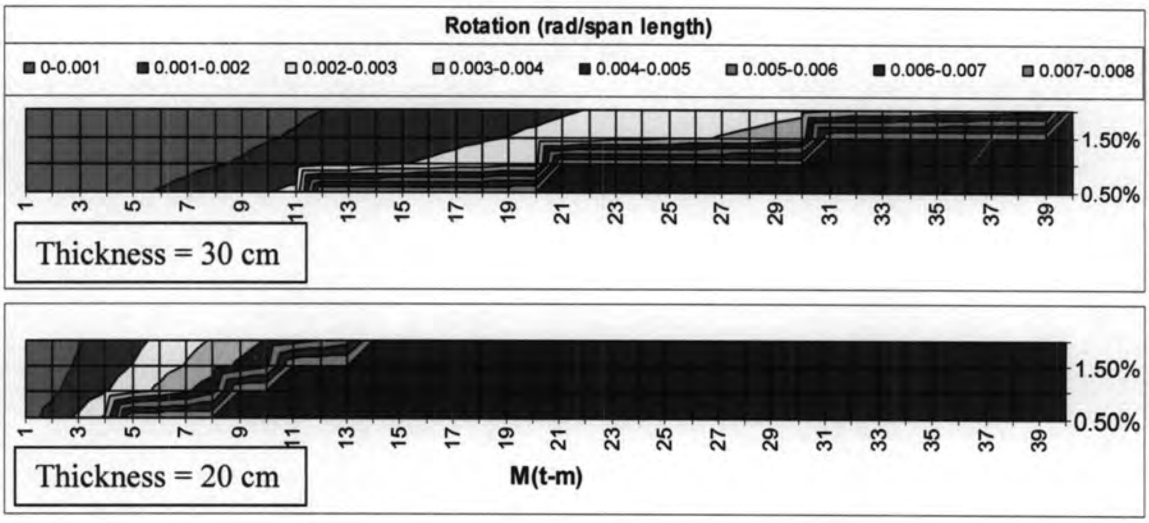
Fig. 5.1 Design approach (continued)



(a) LS_F



(b) LS_S



(c) LS_H

Fig. 5.2 Rotational restraint – moment (per 1 m width) chart