INNOVATIVE INDUSTRIAL FLOOR INITIATIVES FOR JOINTLESS FLOORS: A BONDED POST TENSIONED SOLUTION

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ABSTRACT

Industrial flooring is moving towards jointless applications. The conventional method of jointed slabs is based on controlling stresses by dividing the slab into smaller segments. This method does not, however, allow for long term performance predictions of joints. As the focus is moving towards long term cost effectiveness, innovative solutions must be found to meet these requirements. Post tensioned slab on ground is one such a solution. The advantage of a post tensioned floor is that it increases structural capacity, reduces cracks and can eliminate up to 95 per cent of joints.

1 INTRODUCTION

BMW SA as a client wanted their facility rehabilitated for the launch of their new F30 model. The client re-engineered one of their facilities from a low density to high density stacking warehouse. The intention was to move away from conventional reach trucks to very narrow aisles (VNA) reach trucks. This increased the building storage capacity by 60 per cent. When designing a slab on ground (SOG) for this type of operation, consideration must be given to the Racking height, aisle width and surface regularity.

Common practice in South Africa is to utilize the concept of jointed concrete industrial floors when designing SOG (Marias and Perrie, 2000). The advantage of these systems is the easy installation and the initial lower capital cost. However, these floors need a good maintenance regime in order to keep functioning economically, when viewed from a total operation cost perspective. Further a sound and uniform subgrade condition is required and must be cut into smaller "slabs" to control shrinkage stress (Marias and Perrie, 2000). This is the onset of the main problems as a joint cannot be modelled to predict its performance under service conditions. This often leads to premature failures under repeated and channelled hard wheel loading as induced by VNA reach trucks. This in turn greatly affects both working conditions and equipment performance.

Trends are starting to move more to a jointless or a semi jointless installation, which, greatly reduce long-term maintenance cost for both reach trucks and floor maintenance. Further a more ergonomic friendly environment for the employees with less distress placed on their spines is obtained.

At BMW South Africa in Rosslyn, one such method in the form of a Bonded Post Tensioned (BPT) SOG was implemented. This solution was the first BPT warehouse floor or slab on ground application designed by Nyeleti and considered one of the first BPT

SOG in South Africa. This resulted in a jointless application of 7 000 m^2; within the allowable surface regularity with no cracks or slab curl as found with other solutions such a Steel Fibre Reinforced Concrete (SFRC). The system entailed a double directional tensioned slab put under 2.4 MPa tension. The Post Tensioned (PT) force puts the concrete in compression providing additional structural capacity.

This technology has potential for warehouse floors, terminal areas, hard standings and various other operational areas where low maintenance and structural capacity is essential.

In this application the client was provided with joint less, crack free floor, a first within the plant and a vast improvement on their existing facilities.

2   SURFACE REGULARITY

Surface regularity refers to both flatness and levelness. A flat floor might not be level and a level floor not flat. Therefore the surface profiles need to be controlled so that deviations from the perfect flat line are limited to within tolerable levels for the floors application (TR34, 2000). Figure 1 indicate the difference between flat and level
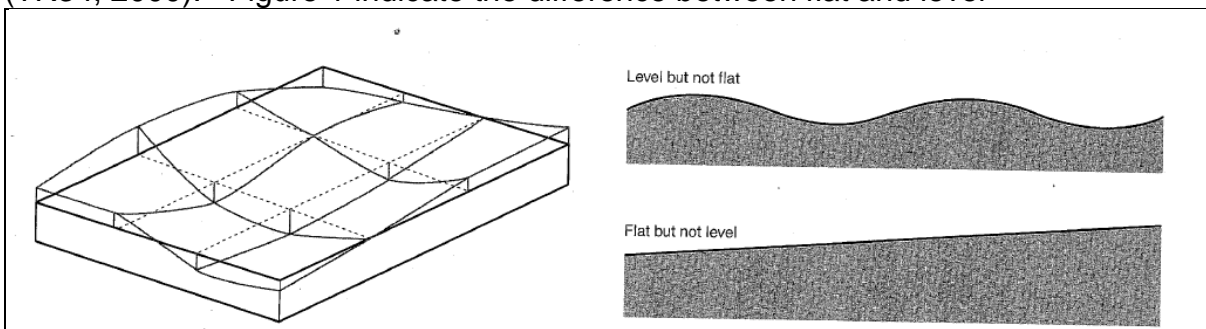
Figure 1: Floor profile, flatness and levelness (TR34, 2000)

2.1   Why "Flat"?

Flat floors ensure a smooth ride for reach trucks operating in high rack and VNA warehouse areas. Even slight undulations and level differences in elevation in the warehouse floor, would make the reach truck operate at less-than-maximum speed when travelling down the aisle, thereby significantly reducing the productivity. Additional poor surface regularity increases the risk of collision between reach trucks and racking, and causes driver fatigue. Stresses created in the mast and body of the truck cause premature failure of welds and disrupt the performance of electronic components (TR 34, 2000).

Figure 2 illustrates the effect of a slight unevenness of 2.5 mm. With property II at 2.5 mm the mast is slanting at 20 mm on a 10 m height. This places stress on the mast and as the Reach truck generally only has 50 mm gap between truck and rack for VNA and can result in collision.

Table 1 and figure 3 indicate the requirements in terms of regularity for floors. Rack heights were up to 8 m at BMW. The specification therefore, required that the defined movement areas be category and the free movement areas FM 3.

In defined movement aisles generally the designer wants to avoid any transverse joints because;
- F-number drops significantly adjacent to any joints, primarily due to slab curl (Marias and Perrie, 2000)

- Gaps at the joints causes bumps when the reach trucks pass over them, causing a rougher ride
- Joint spalling and similar problems would become more common because the reach truck wheels always run in the same tracks.

With PT the transverse joints are coupled joints. This allows a smooth transition without spalling any joints. The joints are not allowed to open as the applied stress from the PT forces it closed.

The movement areas descriptions are defined as follows (TR 34, 2000):
- ***Free movement areas****- can travel randomly in any direction*
- ***Defined movement areas****- vehicles use fixed paths in very narrow aisles.*

Table 1: TR 34 and VNA requirements.

Floor classification	MHE lift height	Property I (mm)		Property II (mm)		Property III (mm)			
						Wheel track up to 1.5 m		Wheel track over 1.5 m	
		95%	100%	95%	100%	95%	100%	95%	100%
Category 2 (CAT 2)	Up to 8 m	2.5	4	3.25	5	3.5	5	4	6
*FM 3	Up to 8 m			5	7.5				

*FM3 require a 3 m grid survey (property IV) to be within limits of 10 mm (95%) and 15 mm (100%)
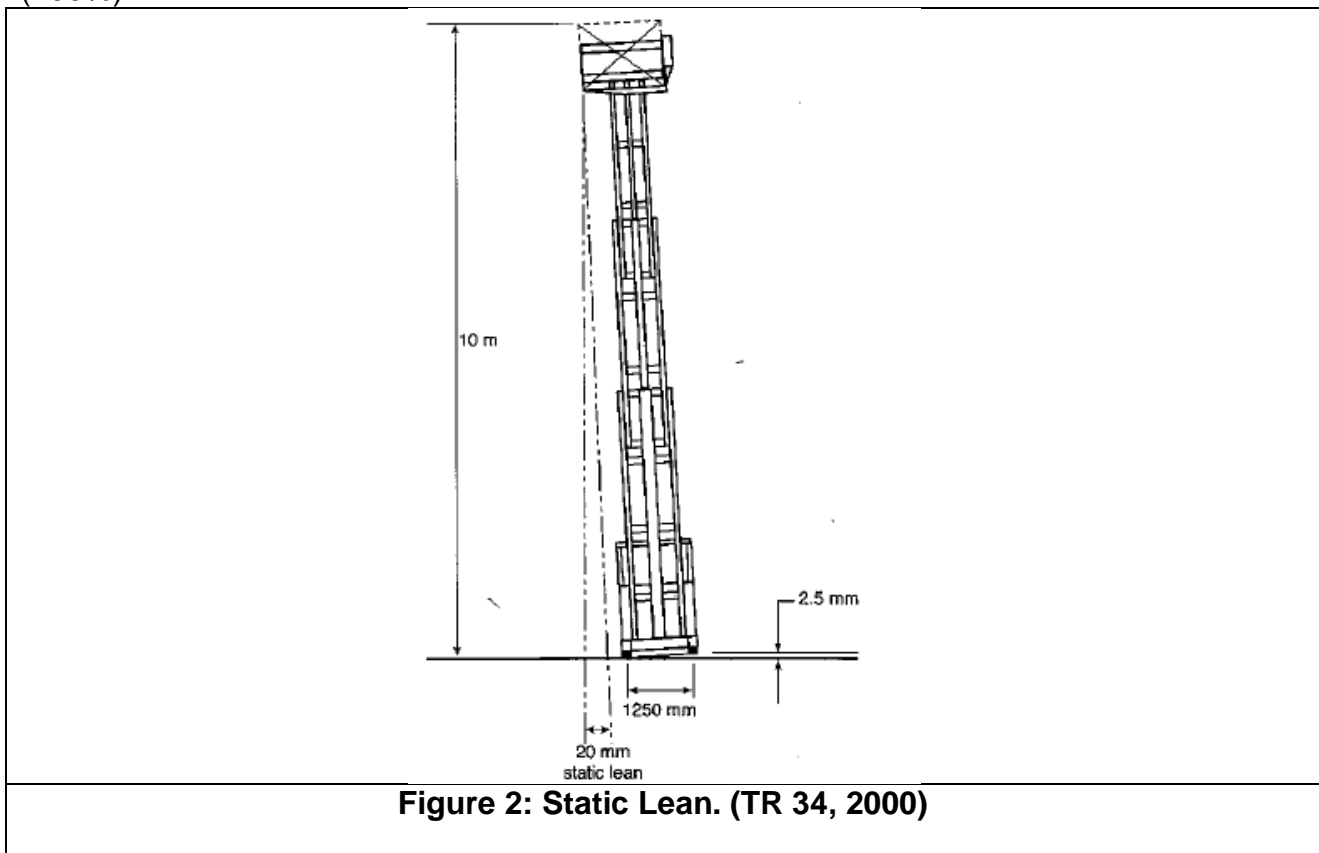
Figure 2: Static Lean. (TR 34, 2000)

Figure 3: TR34 allowable properties for flatness and levelness (TR34, 2000)
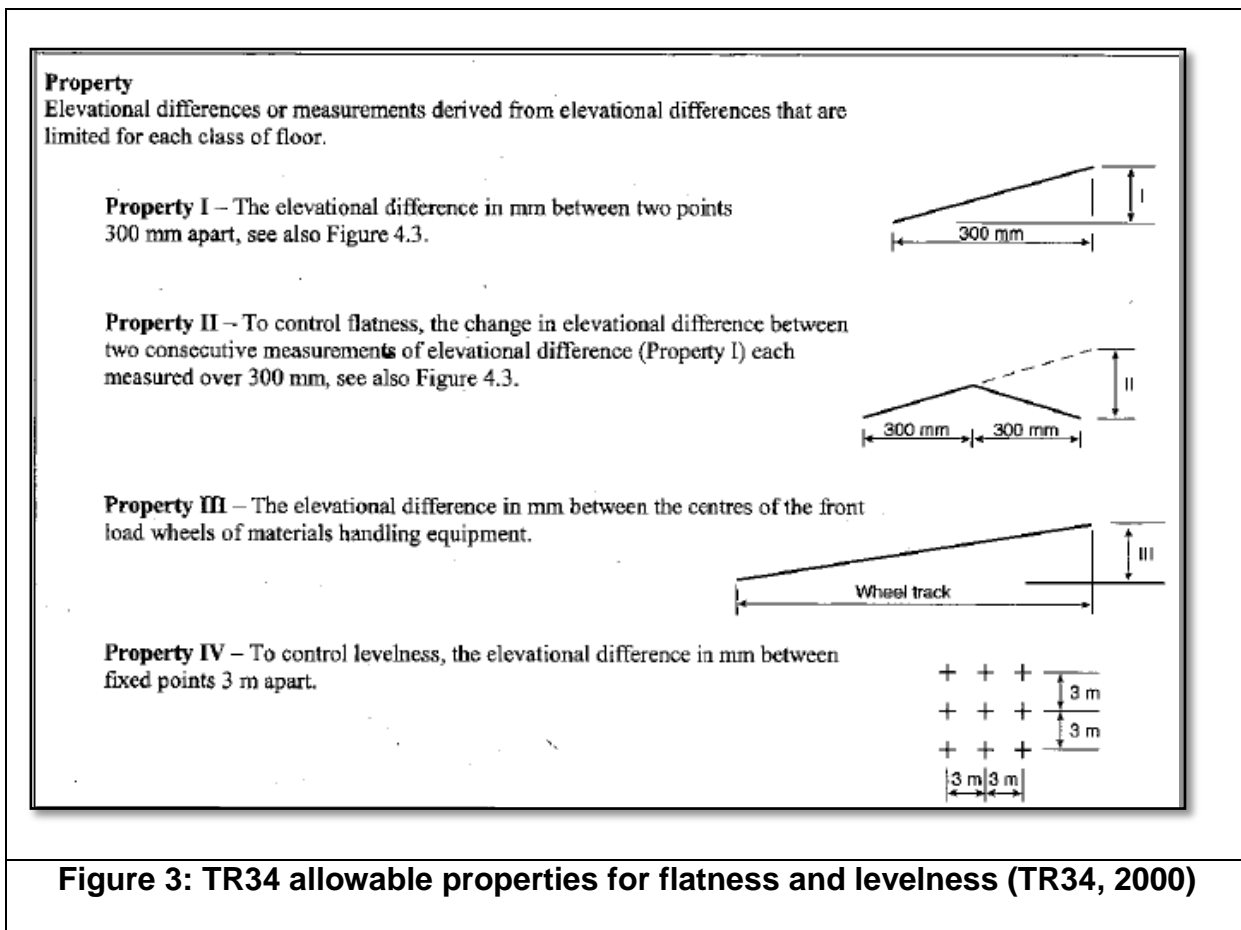
Due to the existing floors distress and poor surface regularity rehabilitation by means of repairs, grinding and self-level screeds was not considered. BMW also wanted to move away from joints as this is a major problem in their plant. Therefore a jointless solution in the form of BPT SOG was proposed.

2.2   Construction constraints

The project consisting of a total of 9 000 m^2 of jointless floor is a challenge in itself; however for this project additional challenges were:
- The plant must be fully operational during construction
- The floor had to be constructed during four phases
- The planning had to include all other service providers including, racking, fire sprinklers etc.
- The building geometry did not allow a boom pump to be used
- The building consisted of column spacing in a 10x10 m grid
- 7 000 m^2 was BPT and 2 000 m^2 was SFRC.

2.3   Layout design

Material handling consideration controlled the design of the facility. The high rack layout dictated the locations of construction joints. The racks were placed back to back at the construction and movement joints. It is important that the racking not straddling the movement joint and thereby tie it. In such a case the joint can crack on either side of the rack or pull the rack out of position.

As the system is automated a guide wire system was installed, which in turn created its own unique problems. These were associated with the detection equipment of the reach trucks used to detect the electronic current of the guide wire and thereby guiding the reach trucks up and down the VNA. The main requirements were that no steel mesh or main reinforcement steel could be within the top 50 mm of the slab. In some stress areas Fibre Reinforce Plastic was used to ensure that the mesh position does not interfere with the guide wire signal.

2.4 Why post tensioned?

As BMW wished to avoid joint and crack problems that plague their entire plant, Nyeleti Consulting proposed a two way BPT SOG. Only coupled construction joints and one movement joint for the 7 000 m^2 area under consideration were designed.

The advantage of post tensioning for industrial floor applications are the reduction in floor thickness and related reduction in concrete cost, elimination or controling of cracking and the elimination of nearly all joints. With reduction in concrete thickness also comes a reduction in carbon footprint making it a greener solution. The post tensioning prevents the coupled construction joints from opening and when constructed properly, PT slabs will not exhibit any significant cracking. The main function of PT is therefore:
- Crack control
- Increased load capacity (Vejvoda, 1993)
- Elimination of 95 per cent of joints.

2.5 PT Slab design aspects

The principles of SOG apply to PT as well as to any other SOG. The information required are the same, which entails loading (wheel and rack), subgrade conditions and support, slab friction, flatness requirements, slab geometry, serviceability requirements. For PT SOG the following must be added:
- PT forces to overcome subgrade friction
- Friction and long term losses in the PT tendons to determine the final effective force
- Short term losses due to tendon grab
- Determination of minimum residual compression to limit or eliminate shrinkage cracking
- Determination of additional residual compression required to meet the allowable tension under load. (Vejvoda, 1993, TMH7, 1981, PTI, 2004)

2.5.1 Thickness determination:
As an example of the design the basic principles are outlined below:

a) Conventional design:
For unlimited traffic the allowable stress ratio would be 0.5. Therefore the allowable flexural or tension stress would be 2.08MPa for a 45MPa concrete mix. Using the design charts presented in Marais and Perry (2000) the slab thickness is calculated as:

- For a 120KN axel load the slab stress is 17.6, and contact area for hard wheels is 29.5 x10^3 mm^2. Using this information the conventional slab thickness of 200mm can be calculated for a subgrade K of 55.

b) Post tension

Using the above data and back calculating the actual slab stress required for a 150mm slab, we find that: Slab stress $\geq$ 29kPa/ kN axel. Therefore the tension stress required can be calculated as: 1.6MPa (PTI, 2004). For various reasons and stress losses the actual stress applied was 2.4MPa.

The tendons were spaced on average at 1.8m centre to entre which when using:

$$\sigma = \frac{P}{A} \qquad \qquad (1)$$

Where
           σ : Stress
           P   : Force
           A   : Area

The force is determined as 632kN per anchor required. With four tendons used the force per tendon is calculated as 158kN. This allowed the anchors to be moved slightly if required as far as 2.3m apart.

Long term stress losses is attributed to:
- Retraction of tendon whilst wedges are being seated (10%loss)
- Creep and shrinkage shorting approximately 10% loss
- Total expected loss of 20% (PTI, 2004) and is shown in figure 4 below
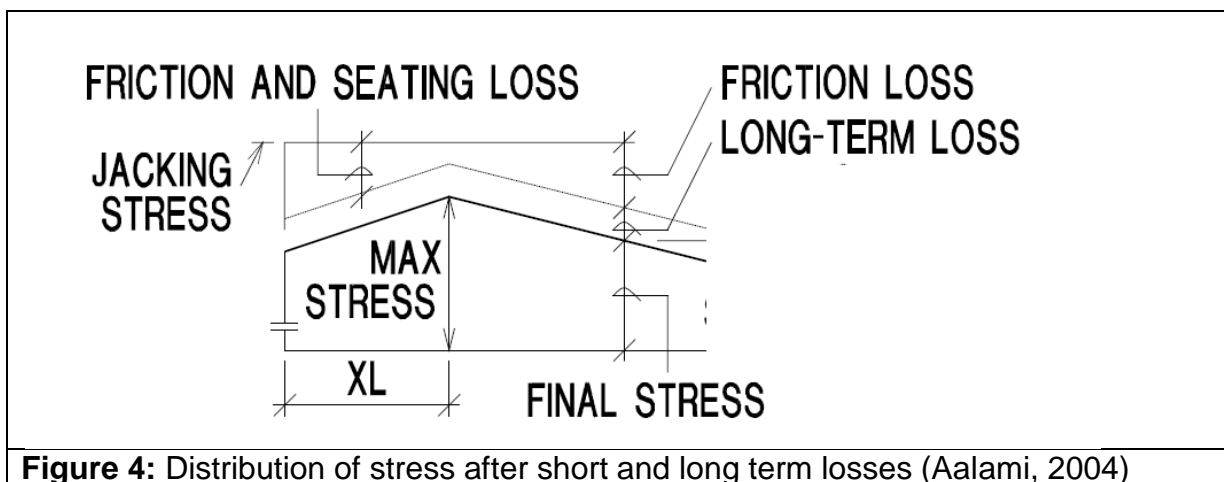
Figure 4: Distribution of stress after short and long term losses (Aalami, 2004)

2.6   Other design considerations

2.6.1 Slab movements

For PT a general rule of thumb for movement is 0.5mm/m of slab, alternatively the actual movement depends on various factors which include:
- Elastic deformation (depended on concrete modulus)
- Shrinkage and creep (depended on time, degree of hardening, environmental conditions, and effective thickness)
- Actual stress applied (TMH7, 1981)

Due to access constraints the floor was constructed in 4 phases of which the first three was BPT and ranged over 5 months. The ensuing sections covers the movements of the BPT section only till January 2012.

For this project the projected movement of 0.5mm/m of slab was used to estimate long term total movements. As the only movement joint was placed at 70 x 65m the movement at the edges of the slab were expected to be 32mm long term, which in turn equates to

16mm per edge on the transverse direction. As Phase 3 was a slab of 35m wide an additional movement of 8.5mm could be expected at the joint totalling a movement of 24.5mm. However, only 12mm has been measured on site. The SOG was, however, cast in phases with up to 8 weeks between phases. This resulted in up to 90 per cent of the total shrinkage / movement taken place between phases (Yetterburg, 1987). The phase / pour sizes are indicated below in Table 2:

Table 2: Pour sizes for building 58.1

| Width Dimensions of phases	Expected shrinkage (mm)
30m	15
35m	17.5
35m	17.5

As the movement joint was between Phase 2 and 3 the revised expected movement would therefore be $\frac{17.5+17.5+15*0.1}{2}$= 18.23mm. The phased approach actually assisted in reducing the total movement at the joint. The actual measurement thus far is 12mm after 60days and explains the large reduction in total movement. The movement is depicted as figure 5.
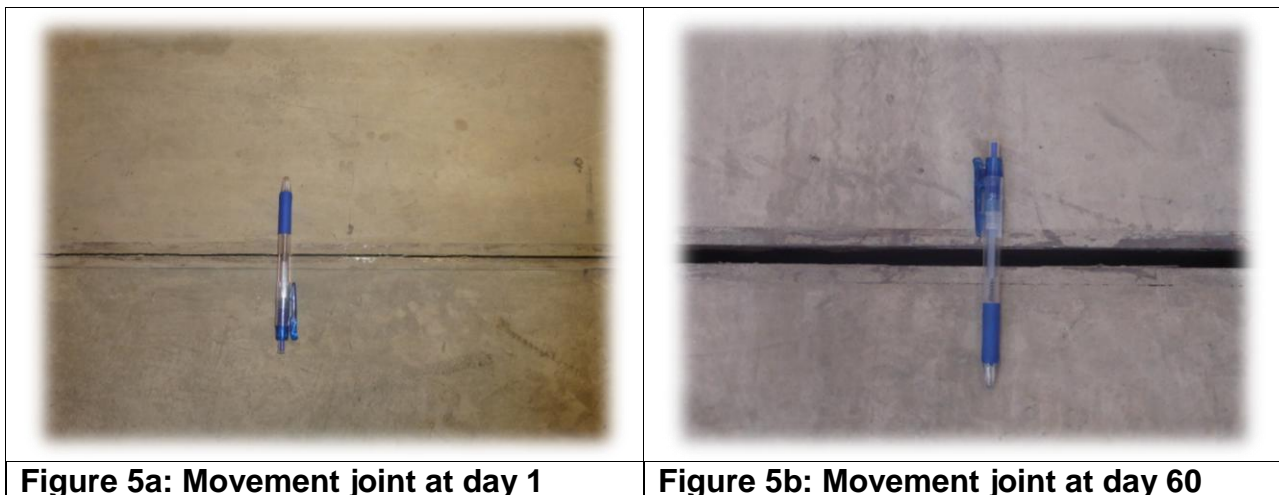
Figure 5a: Movement joint at day 1	Figure 5b: Movement joint at day 60

The data above indicate that the SOG does undergo large movements. Therefore care must be taken to ensure that the SOG is not restricted in any way. RULE ONE in SOG design, is that a restricted slab will crack at the restriction (Marias and Perrie, 2000, Yetterburg, 1987). In this building the column layout presented another concern with a 10mx 10m grid spacing. These are sensitive areas where the slab could "lock" and crack. To overcome this, isolation joints of 30mm thick compressible materials were place around every column, with column reinforcement to reduce stress concentrations. As the movement were expected to be up to 16mm at the edges, the joint material must at least be able to compress to take up these movements. No cracking has taken place at any of the internal columns. An example of this is presented in Figure 6.
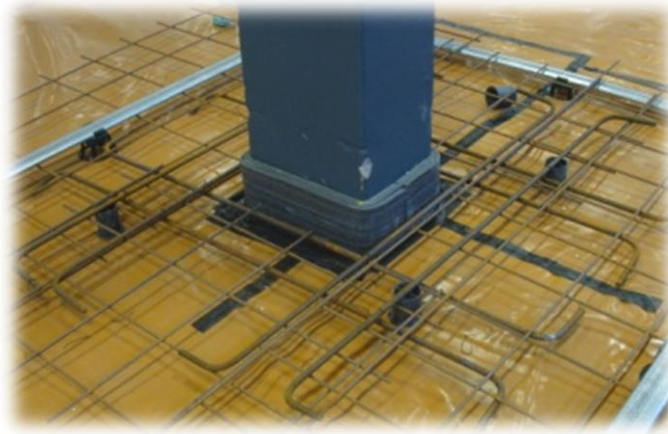
Figure 6: Example of column isolation.

2.6.2 Coupled joints

Significant differential movements between adjacent slabs were expected due to the different placement times and PT stressing. Varying rates of shrinkage, thermal variation and minor differences in modulus of elasticity all contribute to these differential movements (THM7, 1981). All but one joint were coupled and tensioned to ensure that the slabs do not separate, which in turn could spall.

To overcome the applied stresses, the edges were reinforced with Ref. 395 steel mesh, 2.4m wide, in the neutral axis. The applied stress were double with duct spacing done to 500mm, as well as Y20mmØ steel tie bars added at 500c/c and 1000mm long to ensure that:

- The joints are tied
- Differential shrinkage movement controlled
- Stress fractures do not occur on concrete faces.

For this project this approach was successful as none of the coupled joints opened or required epoxy grouting. The edges also did not crack due to any excessive shear stress applied.

2.7   Curling.

Yetterburg (1987) indicted that the PT controls edge curling by placing the concrete under compression. This is accomplished as the compression decreases the natural tensile stresses in the top of the slab, caused by dry shrinkage, whilst, increasing the compressive stress in the bottom of the slab. By doing this the differential rate of shrinkage across the slab depth profile is reduced or eliminated. This in turn reduce or eliminate curling.

Curling is one of the main concerns in warehouse floors and hard standings, as slab crack under load once the support is removed.

2.8   Joints

The movement and entrance joints were reinforced with Perma joints. The Perma joint system is a product which results in a precision milled steel armoured edged joint. This ensures that at the movement joint the reach trucks do not damage the wide open joint. The joint is also filled with MM80, a joint sealant product with a very high shore hardness (in excess of 80). This gives the joint more stability.

3   TENSIONING

In order to assist in the understanding of terms a brief definition is given below:
- **Live anchor** : Tendons are tensioned from this end using a hydraulic jack.
- **Dead anchor:** Dead anchors are on the opposite end of the slab form a live anchor and consist of an onion like structure made from the cable. This ends "grips" into the concrete when force is applied onto the live anchor.
- **Coupled joints**: The tendons are coupled onto a live anchor for the next phase. This anchor serves as a transition between two slabs.

The stressing of the slab was conducted by Structural System Africa, which is specialist subcontractor. The timing of the stressing is of great importance as the initial stress must take place within the first 24 hours of the pour. This is done to reduce the possibility of early shrinkage cracking. By placing the initial stress the thermal shrinkage forces is overcome by the compression induced, thereby eliminating early shrinkage cracking.

The main requirements are that the initial stress can only be done once the concrete has reached 9MPa. At this point 25 per cent of the ultimate break load of the tendon is applied. This should in general be sufficient to overcome any early shrinkage forces but can be calculated. The concrete at 9MPa has gained sufficient strength to withstand the applied stress created by both the live- and dead end not to have live anchors punch in or dead anchors pull out of the concrete

The final stress to 85 per cent of ultimate break (or in this case 158kN) were done once the concrete reached 25MPa. To ensure uniform compression alternate anchors are stressed. 25MPa is required to resist the applied stress transferred from the anchor heads on the concrete to avoid any failures.

3.1   Bonded systems

The PT done at BMW were bonded PT. Bonded PT refer to the fact that the ducts are grouted after the final stressing with a cementitious non-shrink grout. The advantage of such a system is that the slab will not reduce compression if for example a hole is drilled through the duct and tendons after it has been grouted and set.

3.2   What if it fails**?**

The stressing processes are reliant on the concrete strength and soundness on both the dead and live anchor region. If the concrete is not sound or voids are present, the anchor can either slip from the dead end region or crush the concrete from the live end region. Both cases can be fatal if care is not taken at these high forces.

At BMW four of 141 tendons or 2.8 per cent of tendons slipped during the final stressing stages. If this happens and the tendon has not pulled through the duct, it can be reset. This is done by doing a concrete repair, cutting open the dead anchor and resetting the tendon in position. Products such as Prostruct 529 could be used, as high strength quick set concrete to rectify the area and allow stressing within 24 hours.

4   CONCRETE MIX DESIGN

The potential time delay between initial pour to finalization caused concern that the initial stress will not be done prior to potential dry shrinkage cracking takes place. Focusing on stressing times of 24 and 72 hours after final placement high early strengths were required. As the floor was going to be used by hard nylon and neoprene wheeled traffic resistance to abrasion was also critical and strength in excess of 35 MPa after 7 days was required.

To overcome the concern of late first stress applied, the concrete mix was designed to be less prone to shrinkage. The mix contained as low water content as far possible, higher stone content and polypropylene fibres were used at 600 g / m^3. The mix preformed well as no shrinkage cracking (plastic or dry) was observed on the floor.

5   CONCLUSION

BPT SOG was designed and built for a pioneering project at BMW. There are many advantages to a system such as this. For this project, the client was satisfied with the facility. He now had a jointless solution within the required surface regularity specification.

a)   Advantages of this system are:
BPT helps to achieve the following:
- Eliminating shrinkage cracking
- Reduce significantly the number of joints
- Eliminating all control joints
- Reduce the maintenance cost of the floor and reach trucks
- Reduce the initial thickness of the slab and thereby the concrete
- Can be placed on poorer subgrade material than conventional slabs
- Can reduce or eliminate slab curl
- Less concrete mean smaller carbon footprint
- Good planning is essential.

b)   Disadvantages
BPT has however the following disadvantages:
- Time consuming: as each pour has to be stressed fully
- Requires a thin compressible layer below the slip sheet to ensure uniform support
- Only specialized flooring contractors should preferably construct such a floor
- Only specialized post tension suppliers must install and stress the system
- Design is not simplistic
- Good planning is essential.

Bonded Post Tensioned SOG should be considered where a crack, joint free slab is desirable. Where overall durability matters and where potential life cycle cost saving is important. With this solution and due diligence during construction, a high surface regularity specification can also be achieved. With Bonded Post Tensioned SOG significant increases in jointless slabs can be constructed, in this facility 4 500 m^2 jointless and 7000 m^2 with one 70 m linear joint were constructed. .

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