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Office of the Deputy Prime Minister

Enhancing the Whole Life Structural Performance of Multi-Storey Car Parks

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Foreword

The poor performance and premature deterioration of some multi-storey car park (MSCP) structures is leading to disproportionate costs being incurred in remedial works programmes or premature replacement. Concerns about the safety of car park structures expressed by the Standing Committee on Structural Safety (SCOSS) and structural failures, such as occurred at Pipers Row in 1997, have highlighted the need for improved guidance on the inspection, appraisal, maintenance and repair of existing structures. Improvements are also needed to give better whole life cost and sustainability performance in new construction.

The Institution of Structural Engineers (IStructE)[1] and the Institution of Civil Engineers (ICE)[2] are responding to the SCOSS recommendations for the production of improved design and maintenance guidance. In parallel, this Partners in Innovation (PII) research project was initiated by members of the IStructE Task Group and Structural Studies & Design Ltd. (SS&D). This was further developed to meet the needs of the ICE Committee requirements by Mott MacDonald.

The aims of the PII project are to provide analysis of car park structure performance and provide easy-to-follow guidance notes that can be used in conjunction with the IStructE guidance[1] during the design of new car park structures or in conjunction with the ICE guidance when carrying out inspections of existing structures.

In compiling this report over 200 case studies have been reviewed, spanning a range of structure types built over the last 50 years. This report consists of a review of the structural performance of these car park structures, their recurring inadequacies/defects and recommendations for improving the whole life performance of existing and future car park structures.

Multi-storey car park structures have a number of unique features that distinguish them from other buildings. A lack of understanding and recognition of these distinct characteristics by designers and those responsible for inspection and maintenance is believed to be the major cause of many of the common problems identified in these structures. More robust and durable concrete is possible through better detailing, the use of higher quality concretes and improvements in construction practice and supervision. This cannot be achieved by relying on traditional procedures covered in current building codes but should be based on the IStructE recommendations[1] that have been developed by taking into account durability requirements more akin to those for bridge decks or marine structures.

Although the publication of this report marks the completion of the PII study, members of the research team will welcome any comments or further information on the performance of car parks.

[1] "Design of Underground and Multi-storey car parks" 3rd Edition, Institution of Structural Engineers, 2002
[2] " Recommendations for the inspection and maintenance of car park structures", Institution of Civil Engineers, 2002

Acknowledgements

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The project was undertaken by Mott MacDonald Ltd. and assisted by Structural Studies & Design Ltd. in close collaboration with a steering committee.

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Definitions for the Purposes of this Document

Multi-storey car parks (MSCP) — an elevated, multi-storey car park whether self-containing or forming part of a multi-use structure, including any storeys below ground and any bridging or elevated elements essential to the car park.

Structure — primary framework/cores essential to the support and stability of the car park structure, key elements, secondary elements, access ramps and bridges, retaining walls, cladding, vehicular edge protection systems, pedestrian guarding.

Cladding — external components fixed to the structure to protect deck edges, stairs and lift shafts from the weather.

Edge Protection System — a barrier around the edge of a car park deck to protect pedestrians (pedestrian guarding) and/or to restrain errant vehicles (vehicle edge restraint barrier).

1 Structural Performance of Car Parks

1.1 Unique Characteristics/Features of Car Park Structures

MSCP's have a number of unique features that distinguish them from other buildings or structures. A lack of understanding and recognition of these distinct characteristics by designers and those responsible for inspection and maintenance is believed to be the major cause of many of the common problems identified in these structures.

Some of the unique characteristics that make up car park structures are described below.

Car park structures have maximum spans and minimum supports in order to maximise vehicle parking space. The design module for clear span construction is 16m. This is a long span and the dead load:live load ratio is higher than for most other forms of normal concrete building structure. This fundamental design requirement leads inevitably to a far greater risk of cracking and long-term deflections than in other building structures. (see Summary Sheet 9 for further details)

Historically design and construction practice has put an emphasis on minimum first cost and fast construction with simple joints between prefabricated elements. Often these structural forms do not have as much in-built robustness and reserves of strength as more monolithic forms of construction.

Photograph 1 Wide spans & few supports

A car park structure is subject to a substantial live load cycle from full to empty and also to substantial dynamic loadings associated with vehicles moving around the structure. The constant loading and unloading of the structure combined with the normal cyclical movement of the structure due to daily and seasonal thermal and moisture changes develops cracking and articulates joints which can open up pathways for salt and water ingress to accelerate deterioration.

Nearly all MSCP's are open-sided structures with the concrete exposed to cycles of wetting and drying and differential temperatures within and between structural elements. This contrasts with the stable drying conditions in most buildings. The differential strains and movements need to be considered when selecting structural form in design and when appraising the effects of structural movements on strength and deterioration processes in car park structures.

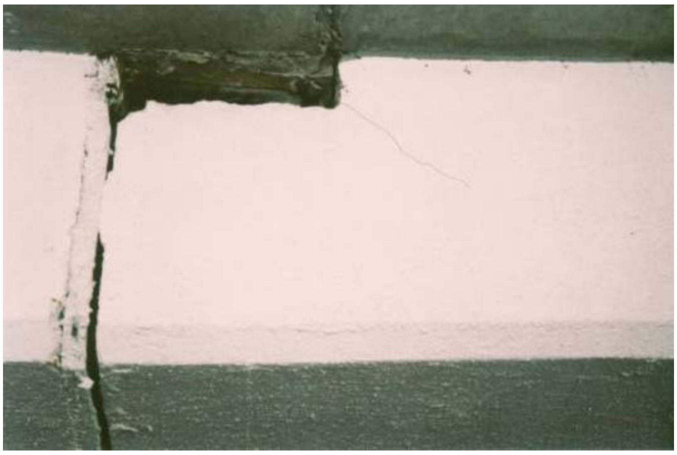
1.2 Quality of Construction

The review of case studies has highlighted poor quality construction as a frequent source of inadequacies in the stock of UK car park structures.

Construction defects can lead to substantial acceleration of deterioration processes by facilitating frost and traffic erosion damage (see *Photograph 2*) and the ingress of carbonation or chlorides to initiate corrosion and by reducing cover. Some construction defects are due to simple bad workmanship on easily constructed elements. However, a significant proportion of inadequacies arise from design forms and detailing which are inherently difficult to construct. A typical example is the half joint shown in *Photograph 3* which, although structurally safe, is under-reinforced. Reinforcement is therefore highly stressed which, combined with short anchorage lengths on the main tensile bars, can result in slight slippage and cracking. This can create a direct route for chlorides and/or carbonation to initiate corrosion of the most highly stressed bars. This is not uncommon and hairline cracking cannot be avoided. But it is possible to control crack widths by increasing the quantity of reinforcement and using smaller diameter bars. It is also essential that due allowance is given to the ease of compaction of the concrete in these design forms.

Photograph 2 Typical example of combined erosion/abrasion and frost damage of a concrete deck.

Some car park structures have shown a great variability of concrete strength and carbonation resistance from pour to pour and within pours due to variation in concrete composition, mixing, segregation and variable compaction. This creates considerable difficulties when core samples are taken as inadequate sampling can miss the low strength areas. Premature deterioration from frost and early spalling indicating rapid carbonation can help identify low quality areas which need to be checked for inadequate concrete strength.



Photograph 3 Typical example of an under-reinforced half joint

Unless there is good site supervision, lowest tender fast construction contracts can increase the risk of misplacing reinforcement. This can be checked during construction with a cover meter, but often shows up 10 to 20 years later as premature corrosion spalling. Low cover can result when inadequately supported slab reinforcement sags towards the shutter leading to premature soffit spalling. The low cover weakens the as-built bond strength, which is further degraded as corrosion spalls the cover. At the top of the slab, high cover from inadequately supported reinforcement can improve durability, but it can lead to increased cracking and most seriously, to a reduction in shear strength in flat slabs for which the factors of safety in BS8110 are inadequate[3].

[3] Wood J G M, "Collapse: The erosion of factors of safety to 0.999", Forensic Engineering: The Investigation of Failures. B. S Neale Ed. Thomas Telford 2001, pp. 185 - 192

Photograph 4 Example of sagging reinforcement, low cover & corrosion spalling

Pre-cast elements have been found to have better quality control on concrete and cover but problems often arise due to poor detailing and/or construction of the topping/screed on pre-cast floor beams. Flexing of reinforced concrete and hogging in pre-stressed elements beams can lead to cracking or delamination of the screed, channelling leakage through joints on to bearing shelves.

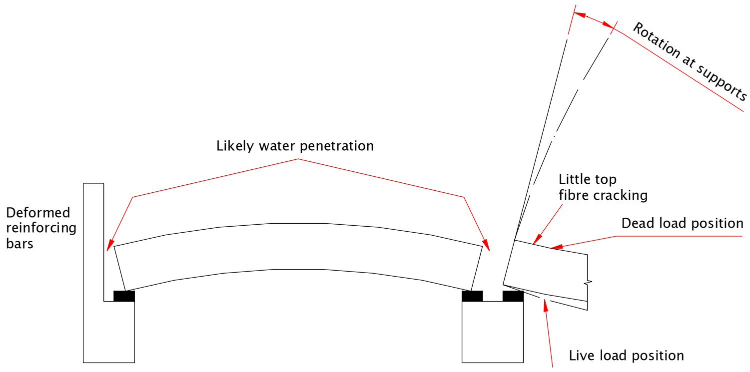


Figure 1 Schematic drawing of type of cracking & deformation due to hogging and creep in pre-stressed elements

Defects have also been found in pre-cast concrete parapet units hung on the edge of concrete slabs or set on stub walls. Dowel pockets are often hastily filled with poor quality mortar and subsequent shrinkage allows water ingress into the dowel pocket which leads to corrosion.

Similar defects occur when poorly cast fixing pockets for external cladding (such as pre-cast concrete mullions) crack and spall.

Photograph 5 Typical example of spalling of poorly constructed fixing pockets used to attach external pre-cast mullion units to parapet walls and deck slabs

Some of the most common construction-related problems identified in the case studies are summarised below:

1. Poor placement of reinforcement – *see Photograph 6.*
2. Poor placing of the concrete
3. Poorly compacted concrete.

4. Inadequate curing of concrete.
5. Premature removal of props and shutters leading to cracking and excessive deflections.
6. Poor casting of movement joints – *see Photograph 7*.
7. Poor falls to the concrete surface.
8. Inappropriate concrete surface finish holding water and salt.
9. Inadequate installation of waterproofing coatings – *see Photograph 8*.

Photograph 6 Typical example of poorly placed reinforcement leading to low cover and corrosion spalling

Photograph 7 Typical example of poorly constructed movement joint suffering premature deterioration

Photograph 8 Typical example of premature deterioration of a waterproof membrane due to defective installation & inadequate crack bridging capability

1.3 Conditions Causing Processes of Structural Deterioration

Structural deterioration and premature failures of car park structures occur as a result of a combination of adverse conditions taking place concurrently, rather than a single process acting alone. The following section represents recurring adverse conditions that have led to premature structural deterioration of existing car park structures over the last 50 years.

1.3.1 Chlorides

A common cause of deterioration in poorly constructed car park structures is associated with the presence of high levels of chloride salts causing corrosion of reinforcement, steelwork and steel fixings.

The case studies reviewed have shown that problem areas for reinforced concrete have developed most rapidly and severely where there is ponding of water, lack of concrete cover, poorly designed and leaking joints, honeycombing and/or other construction-related defects. The case studies have also highlighted the fact that problems associated with chloride attack on concrete are much less severe where movement and construction joints are correctly provided and good compaction of appropriately well designed concrete mixes is achieved.

Analysis of the case studies found that over 50% of structures (the vast majority of these constructed before 1975) had reinforced concrete contaminated with cast-in chlorides. These originate mainly from admixtures containing chlorides (i.e. calcium chloride accelerators) and in a few cases from chloride contaminated aggregates. Cast-in chlorides are a historic problem and in 1977 the maximum amount of chloride permitted by British Standards was substantially reduced[4].

However, vehicles continue to carry and deposit chloride-bearing de-icing salt into car park structures. Analysis of the areas in which chlorides build-up to initiate corrosion of the top reinforcement of typical un-surfaced car park deck slab after approximately 25 years shows that chlorides are concentrated along the traffic tracks and wheel positions in the most frequently used parking bays (see *Figure 2*). These areas of build-up also occur on ramps and within the first one or two levels of a car park structure. The lack of rain wash and the potential for evaporative concentration of ponded chloride-contaminated water in these areas increases the severity of exposure and build-up of chlorides.

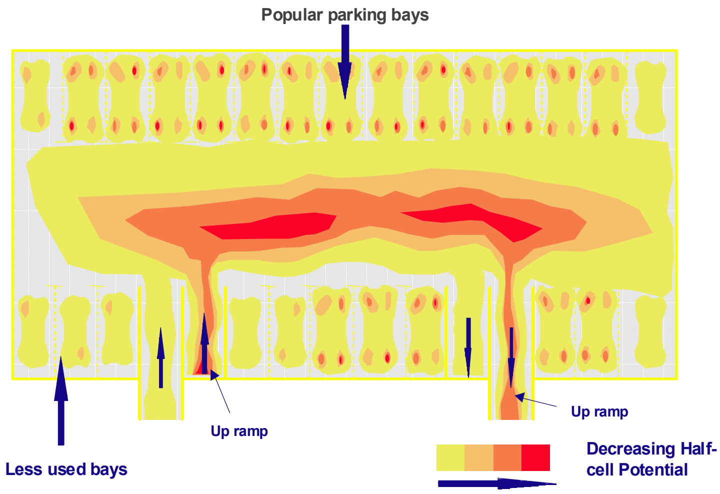


Figure 2 Areas of chloride concentration beneath vehicle tracks

The problems are exacerbated by liberal spreading of chloride-bearing de-icing salts from salt bins within the car park structure. This tends to be a historic problem but the case studies have shown that several car park structures are still subject to salt spreading. In particular, pedestrian areas and walkways in car park structures are often heavily salted to prevent a risk to the public from slipping on

[4] "Concrete reinforcement corrosion. From assessment to repair decisions", ICE Design & Practice Guide, October 2002

ice. In many car park structures much of this risk comes from areas of ponding resulting from sagging slabs, poor falls to deck surfaces and drainage.

Defects associated with chlorides can range from aesthetic concerns (e.g. staining and deposits on soffits, walls, columns, etc.) to structural damage (e.g. localised corrosion and loss of bond strength of reinforcement and spalling concrete). Where chlorides have built up generally in a concrete slab, corrosion tends to develop in patches leading to spalling and delamination. Where the concrete is saturated and chloride ingress is localised, pitting corrosion (black rust) can develop leading to localised and rapid corrosion of reinforcement.

Photograph 9 Typical example of chloride-induced corrosion of reinforced concrete with subsequent dripping of salt water and calcium carbonate onto vehicles below

Steel fixings and steelwork are also prone to chloride-induced corrosion. Mild steel fixings for cladding and edge protection systems are particularly prone to corrosion and can cause failure of cladding and edge protection systems. The case studies found that in many instances the use of galvanised mild steel only delayed the onset of corrosion and did not prevent it from occurring. In particular, galvanised holding down bolts for edge protection systems can be susceptible to corrosion (see Summary Sheet 10).

Photograph 10 Typical example of chloride-induced corrosion of fixing bolts for cladding.

1.3.2 Carbonation

Concrete in car park structures is, like all concrete, subject to progressive loss of alkalinity in from the surface due to carbonation from atmospheric carbon dioxide (CO_2). Atmospheric CO_2 reacts with the cement hydrates to form calcium carbonate, which in turn results in a reduction of the alkalinity of the pore solution. The reduction in pH results in the depassivation of embedded steel and with an ample supply of oxygen and moisture, corrosion can take place rapidly. There are widespread instances of carbonation-induced corrosion developing prematurely in car park structures due to low cover to reinforcement, low quality concrete and/or construction defects. The environment in car park structures cycles between dry conditions, which speed carbonation, and wet conditions, which accelerate corrosion. Cars produce CO_2 from exhausts, but good ventilation generally limits the increase in carbonation rates. However, higher than average levels of carbonation have been observed in city centre car park structures, particularly where air circulation is poor, the ventilation is inadequate and vehicles stand for long periods with their engines running.

Photograph 11 Typical example of carbonation-induced corrosion of reinforced concrete

1.3.3 Frost

Frost (freeze/thaw) damage of concrete occurs mainly on the top decks/roofs of car park structures. Intermediate decks freeze less frequently with the exception of the ground/entry floor where most water and salt solution falls off vehicles on the first two up ramps. Freeze/thaw damage leads to a deterioration of the surface, which then breaks up under traffic. Concrete is only damaged by frost when it is close to saturation so areas of ponding where slabs have sagged and there are inadequate falls or blocked drains are particularly at risk. Rough surfaces, raised speed humps and expansion joints have also been found to create standing water and conditions for frost damage. Under wheel loads frost damaged concrete breaks up creating a pothole in which water sits to aggravate the problem in the next period of cold weather.

Photograph 12 Typical example of frost damaged deck slab on unsurfaced car park roof

1.3.4 Alkali-silica reaction

The damp conditions in car park structures concrete can encourage the development of alkali silica reaction when high alkali cement has been used with reactive aggregates. Current design recommendations [5] [6] provide a basis for minimising the risk by limiting alkalis for this environment while IStructE guidance provides a method for assessing and managing structures with ASR [7]. Waterproofing and improved drainage to minimise availability of moisture and promote drying can slow the reaction and rate of damage.

[5] "Alkali-silica reactions in concrete" BRE Digest 330, 1999

[6] "Alkali-silica reaction: minimising the risk of damage to concrete. Guidance notes and model specification clauses" 3rd Edition, CS Technical Report, 1999

[7] Wood J G M & Johnson R A, "The Appraisal and Maintenance of Structures with Alkali Silica Reaction." The Structural Engineer 71, 2 pp 19-23, January 1993

Photograph 13 Typical example of ASR damage of a reinforced concrete beam

1.3.5 Salt crystallisation

Concrete saturated with salt solutions – e.g. chlorides, sulfates, urea – can suffer from crystallisation pressure damage during periods of drying, particularly where salts are concentrated in an area where evaporation takes place. As water evaporates from within the concrete pore solutions they become increasingly concentrated until saturation is reached. Crystals will then begin to grow within the pore space of the concrete; the resultant stresses ultimately disrupt the matrix of the concrete causing cracking and in the worst cases spalling. Methods to reduce the risk of crystallisation include designing concrete to be dense and impermeable to salt ingress and removing the risk of chloride-contaminated water reaching and ponding on the concrete by providing adequate drainage.

1.3.6 Tyre abrasion

Tyre abrasion/erosion of slab decks is not uncommon in car park structures. The surfaces of concrete decks are subject to continuous movement of vehicles, braking and accelerating. This can cause dusting and wearing of the laitance on inadequate concrete surfaces. A typical example of combined frost and tyre abrasion damage is shown in *Photograph 12*.

1.3.7 Surface finishes

There are a range of textures applied to concrete intermediate decks, ranging from heavily tamped, inconsistent finishes to perfectly smooth, power floated finishes. In heavily textured decks there is a greater risk of holding water and debris which not only reduces the aesthetic appearance of the car park and makes cleaning difficult it can also allow chloride-contaminated water to pond on the concrete surface and permeate through the deck. Heavy tamping may also reduce the cover to reinforcement if carried out badly.

Smooth, power floated finishes on the other hand make cleaning easy and improve the visual appearance of the car park. However, they do promote “tyre squeal”, which is disconcerting for the car park user and surrounding properties. In the presence of water or oil such surfaces become slippery and hazardous for pedestrians and vehicles.

A lightly brushed surface finish, carefully prepared to provide a consistent surface, has been found to provide a relatively easy cleaning regime and adequate skid resistance for intermediate decks.

In modern car parks skid resistant epoxy or polyurethane coatings have been used in intermediate decks. Some coatings available are not full elastomeric membranes and they often do not have the same crack bridging capabilities as the spray-applied or thin, poured epoxy membranes. Intermediate decks can therefore not be expected to be fully waterproof, unless specified to be so. It is however, important to ensure coatings are applied correctly. For example, membranes and coatings should be applied to dry surfaces to avoid blistering and/or delamination of the material in service (see Summary Sheet 6). If properly specified and placed such materials can offer protection against ingress of chlorides and enhance the environment inside the car park.

The IStructE guidance [1] provides detailed advice on concrete finishes and prevention of tyre abrasion.

1.3.8 Car washing

Car washing is sometimes carried out as an additional service in car park structures. It creates a more severe environment as it significantly increases the amount of salt (from the underside of vehicles) penetrating the parking decks. The associated wetting and drying accelerates chloride ingress and corrosion, once initiated. Special waterproofing and drainage provisions are needed in these areas.

1.3.9 Gypsum

A few case studies showed that problems can arise through the misuse of gypsum-based substances used on car park decks for mopping up/removal of oil stains. Although not recommended by the manufacturers for use on concrete, it has been used and has resulted in sulfate attack. The cement paste is destroyed exposing the aggregate, which leads to high abrasion. It also breaks down the bond of some waterproof membranes. It is therefore prudent to test concrete decks for sulfates as part of any testing regime.

1.3.10 Urea

Some car park operators use urea as an alternative deicing method. This has led to cases of deterioration of poor quality concrete by crystallisation and accelerated carbonation as urea breaks down. Recommendations for its use on bridges indicate that concretes over 40N/mm² and rain wash with good drainage to remove urea, are necessary if concrete is not to be adversely affected [8]. The use of urea on pedestrian areas and ramps does reduce the salt chloride load on the concrete. However, work carried out on the Dartford River Crossing [9] and Midlands Links has shown that the carry-in distance for chlorides on vehicles can be 20 miles, so the use of urea in a car park structure may not prevent chloride exposure.

1.4 Original Specification and Design

The specifications for concrete in current design standards for buildings have been found to be inadequate to achieve long term durability in car parks where there is poor detailing and drainage. In the 1960s and 1970s specifications permitted lower strength concrete, higher water cement ratios, lower concrete covers and poor construction quality compounded the problems. For many car park structures low cost and fast build had a greater priority than construction quality.

[8] Sadagzadeh M and Page C L, "Effects of Urea on the durability of reinforced", TRRL CR 208 Digest, 1990
[9] Mott MacDonald Reports, "Monitoring of salt carry-over loads on Dartford Crossing", Oct 1991 – Mar 1997

For car park structures designed in the 1960s, calcium chloride was a permitted admixture so some structures invariably had built-in problems. During the boom in car park construction during the late 1960s and early 1970s, 'design and build' contracts were frequently used based on building standards and specifications less demanding than was appropriate for the achievement of durable structures. The common structural codes that have historically been used to design car park structures are shown in Table 1. Present day codes commonly used in car park design include BS8110 and BS6399.

Table 1 Common structural codes historically used to design car park structures

Code	Title	Published Date
CP 3, Chapter 5, Pt 1	Loading – Dead and imposed loads	1952, 1967*
CP114	The structural use of reinforced concrete in buildings	1957
CP115	Prestressed concrete in buildings	1959
BS449	Structural Steel	1959
CP116	Pre-cast concrete	1969
CP 3, Chapter 5, Pt 2	Loading – Wind loads	1970, 1972
CP110	Structural use of concrete	1972
BS8110	Structural use of concrete	1985, 1997
BS6399 Part 1	Loadings for buildings: Code of practice for dead and imposed loads	1996
BS6399 Part 2	Loadings for buildings: Code of practice for wind loads	1997

* Amended 1972 to include vehicle impact

The study has found that pre-existing design standards and Codes of Practice to be inadequate in respect of classification and treatment of exposure conditions, impact forces and progressive collapse of the structure.

For example, the CP114 empirical rules for flat slabs were withdrawn as the shear rules were inadequate under certain conditions. This is a particular problem with flat slabs, often compounded by unusual detailing and poor construction. BS8110 provides a better basis for appraisal but effects of detailing and shear heads outside the scope of the standard need special consideration[10 11].

Photograph 14 'Opening-up' of column in a lift slab structure where bottom reinforcement does not extend to the lifting collar, nor is it properly anchored

[10] "Pipers Row Car Park", Kellerman J, Concrete Car Parks Conference, BCA, Sept. 1997
[11] "Interim results of Pipers Row investigation", Health & Safety Executive Press Release, 30 April 1997

It should also be noted that although the average vehicle weight remains the same at 2500kg which, allowing for impact, equates to a uniformly distributed load of 2.50kN/m², the localised effect of impact on ramps should be considered where the ramp gradient exceeds 1 in 7 (see IStructE[1] report for further details).

As a general comment neither BS 8110[12], nor Eurocode EC2[13], contains exposure conditions which match car park structures and it is left to the designer to determine the degree of exposure and specify the concrete properties. Historically the designer did not consider the severe exposure conditions or was under commercial pressure to design down not fully understanding the long-term effects of chloride attack, etc.

1.4.1 Inadequacies in Design

The review of case studies highlighted several inadequacies in the original design of car park structures. Some of these relate to the use of inadequate (now superseded) standards and codes of practice. Others have arisen from the use of "innovative" construction systems that lie outside the scope of design codes where the effects of tolerances and misfit of pre-cast elements have not been fully considered. The majority of these design inadequacies have been addressed in the latest design guidance from the IStructE[1]. However, it is necessary to emphasise these points since they need detailed consideration in the appraisal of existing car park structures.

The most common design inadequacies identified in the case studies include:

1. Inadequate robustness against progressive collapse

Where structures have a high degree of redundancy and ductile modes of failure there is little likelihood of the collapse of an individual member and even less of it developing into a progressive collapse. However, car park structures have a variety of structural forms and are in some instances not inherently robust as-built with ductile failure modes. Deterioration or construction defects can also lead to a loss of ductility. The simplified BS8110[12] rules for ties for robustness do not necessarily ensure robustness with all forms of flat slab construction and some other structural forms found in car park structures[3].

2. Inadequate design of joints and tolerancing to accommodate movement

The amount of movement to be accommodated by a movement joint is often under-designed. Major problems can arise due to the lack of or inadequate number of thermal movement joints. Cracks often open up at day joints because these act as weak spots for the formation of natural construction joints. Lack of adequate tolerancing can make the problem worse and tolerance and movement need particular care where the seating on to bearing shelves is small. Generally designs have not taken into account the types of movement car park structures are subject to during and after construction. Inadequately designed joints are not capable of withstanding this movement and sealants break down allowing water and salts to get into the joints and cause deterioration.

3. Inadequate drainage falls

In existing car park structures a combination of inadequate design for the disposal of rainwater combined with poor standards of construction and concrete finishing leads to ponding.

On decks, the minimum falls to the concrete should be 1:60 and there should be sufficient outlets to cope with the high volumes of water expected in downpour conditions. Decks with shallow gradients

[12] BS8110 : Part 1 "Structural Use of concrete – Code of practice for design and construction", 1997, BSI

[13] "EuroCode 2: Design of Concrete Structures, Part 1-1: General – Common rules for building and civil engineering structures", EN 1992-1-1

and minimum rainwater outlets generally develop ponding due to errors in construction levels, deflections and/or creep. Ponding can lead to the collection and concentration of chlorides and to areas of frost deterioration, as well as a safety hazard in freezing weather. The safety hazard is frequently dealt with by liberal application of chloride-bearing de-icing salts, which can lead to further deterioration. Where water runs off the end of a slab an adequate drip detail is required to ensure a reduction in the movement of water across the slab.

4. Inadequate concrete specification and cover to reinforcement

During the 1960s and 1970s concrete specifications for car park structures permitted the use of higher water/cement ratios, lower strengths and low cover to reinforcement than is required for durable concrete. The ambiguity in the definition of exposure conditions in these codes also led to designers specifying inadequate cover and/or concrete strength. The majority of concrete-related durability problems relate to ingress of water and chloride salts so designing low permeability concrete is more important than high strength. There is some evidence that, in recently constructed car park structures, high strength concrete and corresponding lower covers have been specified. This has led to excessive heat of hydration, early-age cracking and durability problems. However, experience has shown the type of concrete should be designed to suit not only the serviceability requirements but also the thickness of section, density of reinforcement, time of year of construction, contractor's working methods, etc. Further details on enhancing concrete specification and concrete cover are given in the IStructE guidance report [1].

5. Inadequate detailing of reinforcement and errors in steel fixing

The case studies have shown that in several structures the reinforcement detailing does not match the designer's intent and indeed steel fixing bears little resemblance to the reinforcement drawings.

6. Substandard waterproofing specification details

Specifications for waterproofing coatings require careful consideration and an understanding of the material and structural requirement of the material. The service life of coatings can be severely reduced by solar radiation, de-icing salts, fuel and oils, shrinkage hardening and embrittlement. All too often substandard coatings are specified and selection is too often based on lowest price rather than proven service performance. For example, there are numerous examples of materials with low crack bridging capabilities being specified and failing 1 to 3 years after installation (see Photograph 8). Poor application procedures and workmanship and application in unsuitable weather have also contributed to premature breakdown.

7. Inadequate fixings of cladding/edge barriers

In many car park structures pre-cast concrete parapet units are hung on the very edge of the concrete slab or set on stub walls. The general method of fixing is by dowel bars and on many older car park structures dowels were under-designed and/or of an inadequate material. Chloride-bearing salts readily corrode mild steel dowels and severe corrosion can lead to pre-cast units being pushed off the edge of the deck. Stainless steel dowels have the potential to substantially increase resistance to corrosion. However, the potential for bimetallic corrosion should be carefully considered.

8. Inadequate strength of edge protection to restrain errant vehicles and fixings.

There has been a series of accidents in recent years when drivers have lost control of their vehicles in car par structures, breaching crash barriers and plunging to the ground. A comprehensive appraisal programme of edge protection has been undertaken at Cranfield University, assisted by TRL Ltd.[14] [15]

[14] "Edge protection in multi-storey car parks – design, specification and compliance testing", Third report produced under DTLR PII Scheme, Contract Ref. 39/3/570/ CC1806, 2001.

[15] "Edge protection in multi-storey car parks – assessment of installed restraint systems", Fourth report produced under DTLR PII Scheme, Contract Ref. 39/3/570/ CC1806, 2001.

where further detailed information on edge protection in car park structures can be found. Updated design information is also available in the new IStructE guidance document [1].

9. Excessive deflections and poor geometry leading to ponding.

Another cause of ponding is the normal development of creep deflections in beams and slabs which are set with an inadequate fall to compensate for the inevitable deflection. Creep deflections can be increased by high cement contents, high water cement ratios and premature removal of props and shutters.

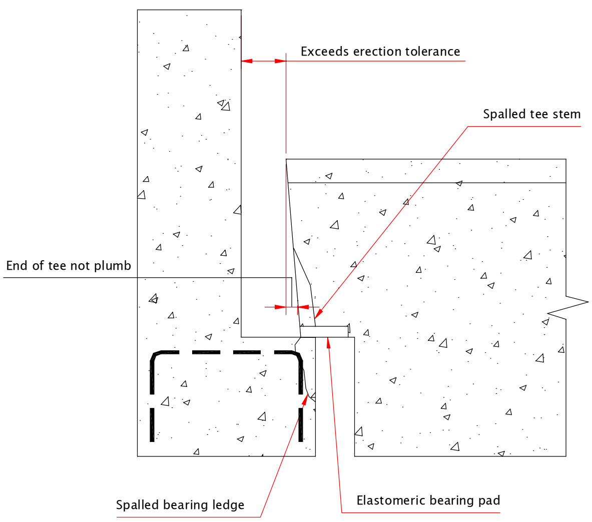
10. Development of seepage paths through cracks, at day work joints and between pre-cast and in-situ concrete.

Day work joints and in situ concrete cast against pre-cast elements often create seepage paths into the structure. There are two reasons for this. The first is that the full compaction of concrete being cast against a flat surface is difficult to achieve, with a tendency for honeycombing to form. Local compaction needs to be thoroughly carried out along the joint. In car park slabs this requires a higher level of workmanship than in office building floors in a benign environment. The second problem arises from the formation of a crack at these relatively weaker joints due to thermal shrinkage and structural movements of the car park structure.

1.5 Critical Locations

The review of case studies highlighted areas within car park structures that are critical due to their structural form, environment or a combination of the two.

Critical locations due to structural form and vulnerable to corrosion are seldom at the locations of maximum stress for which main flexural reinforcement is sized in design. Structural damage influencing strength, stability and resistance to progressive collapse most frequently arises from loss of bond strength and anchorage as cover is spalled by corrosion or lost from frost or traffic erosion. Such is the variety of structural forms found in car park structures that no general checklist is appropriate. The reinforcement drawings need critical review with an eye to the interaction of deterioration with actual structural behaviour. Some examples are indicated below.



Corrosion of the bottom steel of pre-stressed or reinforced beams with limited seating onto a ledge can split along the reinforcement creating a risk of the beam ‘falling off its perch’ (see Figure 3). Corrosion and spalling in the corbel or ledge may aggravate this. The preferential corrosion at the corners of column stirrups can lead to failure and loss of bond over the critical lap length.

Pre-stressed and post-tensioned concrete are more susceptible to chloride-induced corrosion because the corrosion initiation threshold is only 0.1% (Cl by weight of cement) compared with 0.4% for reinforced concrete.

Figure 3 Schematic sketch showing corrosion of bottom reinforcement & associated spalling of tee stem and bearing ledge

Saturated chloride contaminated concrete, as in seeping half-joints can lead to very severe localised pitting corrosion of flexural and shear steel and loss of bond and anchorage. Reinforcement tying edge beams into the screed over pre-cast beams can similarly corrode when salt seeps through the joint. Shear stirrups can lose all effectiveness when their side laps spall or corners corrode through.

Photograph 15 Typical example of a seeping half-joint

Punching shear resistance depends on the dowel action and anchorage of the top reinforcement around the shear perimeter. Degradation by frost and erosion of the cover above the reinforcement will progressively weaken the bond, which is then destroyed when corrosion spalls or delaminates the cover. Inadequate factors of safety in old codes and in BS8110 [12] make this a particularly sensitive failure mode, as does the progressive failure that follows [3 16]. However if properly designed, detailed and constructed, fully considering those innovative features which are not explicitly covered in standards, all structural forms, including lift slab structures, are satisfactory. The resistance to progressive collapse in flat slabs is negligible in the absence of at least 25% of main bottom steel being carried through or positively anchored to the column heads. This is not yet a requirement in BS8110 [12] and needs careful consideration in both design and appraisal.

Photograph 16 Example of column head shear failure at Piper's Row

In many structures much of the concrete and a proportion of the reinforcement is of negligible structural significance. Non-structural degradation in these areas can be tolerated until aesthetic considerations or declining user confidence necessitates action.

Some examples of locations critical due to environment are listed below:

[16] Health & Safety Executive Reports on Pipers Row Partial Collapse, Wolverhampton, 1997

Bottom of ramps Salt water can collect at the bottom of the ramp and on steep ramps impact damage and wear can take place. *Refer to Summary Sheet 1 for further information.* *Photograph 17 Typical example of wear to the bottom of a ramp aggravated by the effects of impact damage and ponding of water at this location*	

Movement joints They leak allowing salt water to access other areas of the structure	*Refer to Summary Sheets 3 & 4 for further information.*
Day-joints in ribbed slabs Many are badly constructed and allow leakage of water and salts. *Photograph 18 Typical example of leakage through a day-joint in a ribbed slab*	

Beam ends on ledges Salts absorbed into end anchorage and bearing length of beam	*Refer to Section 1.5 for further information*

Bearing shelves and corbels Joint seepage concentrates chloride-bearing water on the bearing shelf/corbel and initiates corrosion and spalling *Photograph 19 Typical example of joint seepage & corrosion on a bearing shelf*	

Columns Splash of salt from adjacent ponding onto lap length and stirrups *Photograph 20 Typical example of corrosion within the bottom area of a column*	

1.6 Proven features of good performance

The case studies highlighted several features within structures that have accounted for good performance. Many of these features have been adopted with the IStructE design guidance report [1]. A summary of proven features of good performance is given below.

- Where car park structures are well waterproofed, have good falls, are washed down periodically (especially after periods of cold weather) with good drainage systems, the chloride is channelled away from the concrete and there is a reduced risk of chloride-induced corrosion from developing
- Where water proofing is absent, but there is a good cover (40mm minimum) to the reinforcement and a well compacted and cured surface of 45 + N/mm² concrete, free of ponding and with good overall falls and no roughness to hold water and salts, some car park structure decks have lasted over 30 years with no apparent corrosion problems occurring from chlorides.

- Drainage paths should be not be interrupted by joints or kerbs – even line/bay markings can impede drainage runs.
- Joints should be located at high spots in the decks, never at low points or where surface water has to cross over them.
- If joints have to be in the running areas and have to be sealed use a good quality proprietary type joint and maintain it.
- If the joint does not have to be sealed, avoid a complex joint and put in a slot in the deck and collect water in a detachable gutter below with drips to avoid leakage running under the soffit.

2 Inadequacies/Defects Often Found in Existing Car Park Structures

The previous sections have provided details on recurring inadequacies and deterioration of critical structural forms that have affected the durability and structural performance of existing car park structures over the last 50 years and which ultimately reduce whole life performance.

In order to provide easy-to-follow guidance notes that can be used in conjunction with the IStructE guidance [1] during the design of new car park structures or in conjunction with the ICE guidance [2] when carrying out inspections of existing structures this section provides a summary of the most important recurring defects. It also provides a few examples of typical inspection procedures.

Table 2 provides a summary of the content of each one-page best practice summary sheet. These summary sheets describe sensitive structural details, elements, form of construction, materials, etc. Each sheet includes a typical photograph and/or sketch. Guidance is provided for avoiding problems through design, inspection-related information, best practice maintenance and repair options, etc. There is also a list of references that can be obtained for more detailed information/guidance.

Table 2 Summary of inadequacies/defects often found in existing car park structures

Common Inadequacies/Defects	Summary Sheet Ref. No.
Structure	
Drainage – bottom ramp drains.	1
Double tee/in-situ concrete edge beam.	2
Deterioration of joints.	3
Under-design of joints to accommodate movement.	4
Incorrect placement and insufficient waterproofing of channel gullies.	5
Deterioration of waterproofing membranes/coatings	6
Cracking and corrosion of deck slabs	7
Typical problems with steel decks, pre-cast concrete and hollow core units	8
Common types of cracking	9
Edge Protection Systems	
Barrier fixings – holding down bolts	10
Lack of cover in in-situ and pre-cast parapet walls due to thin concrete sections.	11
Typical Example of Inspection and Assessment of MSCP	12
Typical Example of the Application of a Cathodic Protection System	13

Summary Sheet 1
Drainage - bottom ramp drains

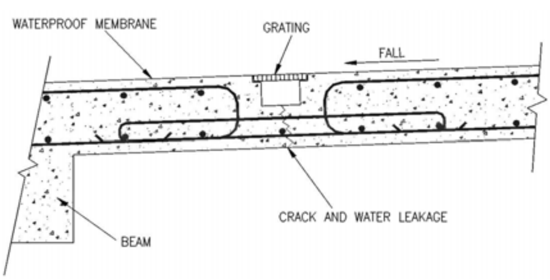
Brief Description
- Drainage details at the bottom of ramps often take the form of a channel cast into the concrete slab with a metal grating.
- This type of drainage channel is difficult to lay to falls and suffers from standing water and eventually silts up.
- Longitudinal cracking is known to take place in the bottom of the channel, which is sometimes accompanied by transverse cracking at about 3.0m centres.
- Waterproofing is difficult to apply up to the face of the channel or breaks away when damaged by the metal grating.

Potential Effects on Durability & Structural Performance
- Ponding of chloride-contaminated water onto decks and ramps.
- Vulnerable to freeze-thaw attack.
- Slip hazard

Recommendations for Design for Enhancing Durability
- Line the channel with an elastomeric coating, which will accommodate any movement.
- Particular care is required in the detailing of the coating around the metal grating at the top of the channel.
- Ensure channel is kept free of debris and allows effective drainage of water.

Identifying Potential Inadequacies/Inspection Information
- Remove grating and clean out to facilitate visual inspection of the bottom of the channel.

Typical installation showing an open end channel allowing water to discharge onto an adjacent deck



Typical drainage channel detail

Example of water ponding

References for Detailed Recommendations

1. "Design recommendations for multi-storey and underground car parks" IStructE report 3rd edition, 2002.

1. "Recommendations for the inspection and maintenance of car park structures" ICE, 2002.

Summary Sheet 2
Double tee/in-situ concrete edge beam

Brief Description

- The use of wide span, double tee beams is widespread.
- Case studies have shown that cracking inevitably occurs along the abutment of these units.
- As this cracking is not anticipated in the design, finishes are not designed to accommodate the movement and water penetration occurs.
- Any water flowing toward the drainage channel has to cross the crack inducer/sealer, which, if not 100% effective, can cause water to leak down the half joint and corrode the dowel bars and the bearing pads. Corrosive water then drips onto the cars below.
- Other problems observed include inadequate bearing length, point bearing and significant lateral forces at the bearing, which cause spalling of the corners of the ledge or tee end.

Potential Effects on Durability & Structural Performance

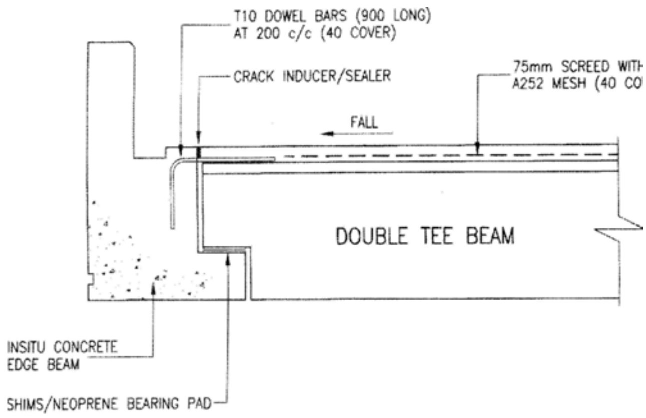
- Inadequate bearing length, point bearing and significant lateral forces at the bearing, which cause spalling of the corners of the ledge or tee end.
- Chloride –contaminated water from de-icing salts can leak through these areas leading to corrosion of reinforcing steel and cracking and spalling of concrete.
- Corrosive water then drips onto the cars below.
- In some instances dowel bars have to be bent up to allow the double tees to be installed. This not only weakens the bars but also contravenes the CDM Regulations when the bars are bent up.

Recommendations for Design for Enhancing Durability

- Make the connection between the in-situ and the precast double tee a fixed connection and make the connection at the other end of the double tee a free movement joint. This then puts the movement joint at the drier end of the double tee.

Identifying Potential Inadequacies/Inspection Information

- Ensure careful inspection of bearing pads and leading edges.



TYPICAL INSITU/PRECAST DOUBLE TEE BEAM SUPPORT

Example of seepage bewteen precast beam & in situ wall

References for Detailed Recommendations

1. “Design recommendations for multi-storey and underground car parks” IStructE report 3rd edition, 2002.

1. “Recommendations for the inspection and maintenance of car park structures” ICE, 2002.

Summary Sheet 3
Deterioration of joints

Brief Description

- Joints in car park structures experience similar environments to bridge grade joints and are therefore structurally important.
- Joints are subjected to chloride attack and carbonation caused by the environment in a car park.
- Water seepage through the joint is also a common problem.
- A way to prevent these attacks degrading the properties of the reinforced concrete would be to apply waterproofing systems or raise the joint so as to allow water to run off.

Potential Effects on Durability & Structural Performance

- De-icing salts containing chlorides can seep through joints. This, and the increased presence of water, promotes corrosion of the rebar and eventually delamination and spalling of covering concrete and pitting corrosion.
- Carbon dioxide from the atmosphere neutralises the concrete allowing the passive film on the surface of the steel to break down. Delaminations and spalling can occur as above.
- Increased likelihood that reinforcement corrosion will have affected the structure

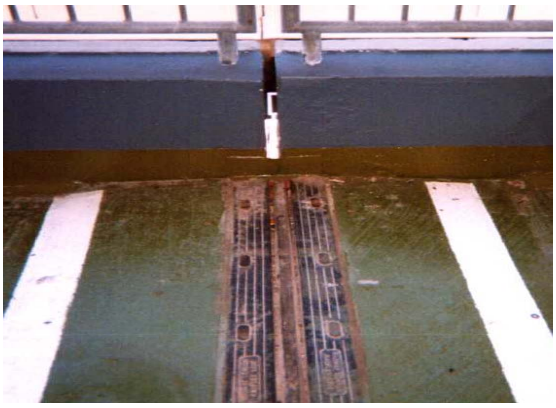
Recommendations for Design for Enhancing Durability

- Joints should be included in any waterproofing system.
- Raised joints can be constructed to allow water to run off and not penetrate.

Identifying Potential Inadequacies/Inspection Information

- Carry out visual inspections of the structure in wet conditions, if possible, and note seepage and discolouration.
- Also use a boroscope in areas which are not exposed to view.

Degraded joint area



Raised joint prevents water runoff from entering the joint

References for Detailed Recommendations

1. "Design recommendations for multi-storey and underground car parks" IStructE report 3rd edition, 2002.

1. "Recommendations for the inspection and maintenance of car park structures" ICE, 2002.

Summary Sheet 4
Under-design of joints to accommodate movement

Brief Description

- Although there are many types and designs of movement joints and many new designs of joint are being introduced, they still provide some of the most challenging areas in design.
- The amount of movement to be accommodated in the joint is often under-designed and when a joint is specified which is operating at its limit for the designed movement, it usually fails when this movement is exceeded.
- Water seepage through the joint is also a common problem.

Potential Effects on Durability & Structural Performance

- Many movement joints use a butyl rubber strip bolted down into a recess to span the potential movement.
- The main point of weakness has been found to be where the holding down bolts penetrate the waterproofing membrane on the car park roof.
- This leads to puncturing of the membrane and eventual water ingress.
- The fixing of such joints is extremely complex and slow and there is no guarantee or certainty of waterproofing even when installed.
- Increased likelihood that reinforcement corrosion will have affected the structure.

Recommendations for Design for Enhancing Durability

- Flow of water over joint seals should be minimised by using sloping surfaces and correctly located and designed drains.
- Seals with wide installation tolerances are desirable due to the difficulty in predicting actual joint movements.
- The ability to keep joints clear of debris or to remove debris is also important for effective joint behaviour and ease of maintenance.

Identifying Potential Inadequacies/Inspection Information

- Note evidence of degradation of joint materials.
- Look for evidence of leakage from soffit areas, be aware that signs of leakage could be some distance from the damaged area of waterproofing – water may track for some distance under the waterproofing.
- Check reinforcement location and the tolerancing of the seating of beams on corbels/ledges against as-built drawings.

Failed joint with water ponding

Water leakage from failed joint as viewed from the underlying soffit.

References for Detailed Recommendations

1. “Design recommendations for multi-storey and underground car parks” IStructE report 3rd edition, 2002.

1. “Recommendations for the inspection and maintenance of car park structures” ICE, 2002.

Summary Sheet 5
Incorrect placement and insufficient waterproofing of channel gullies

Brief Description

- Effective management of water drainage requires correctly placed gully outlets.
- Gully outlets often placed in the wrong position to provide adequate drainage.
- Box-outs are often left in the slab laying process for the fixing of gullies at a later date.
- When the gully is concreted in place a poor quality, uncontrolled mix is often used which inevitably shrinks leading to cracking in the deck around the perimeter just where water concentration is at its highest.

Potential Effects on Durability & Structural Performance

- Differential movement between the gully and the surrounding concrete is a major potential source of water ingress. As the concrete dries and shrinks away from the plastic or metal gully a small fissure is created allowing water to drip from the underside of the gully fitting on to the lower deck.
- Ponding of water sometimes arises because the gullies fixed at a later date are sometimes placed higher that the surrounding concrete.
- Ponding of water around gully outlets placed adjacent to columns is concentrated around the base of columns which could lead to corrosion of reinforcement in this structurally sensitive area.

Recommendations for Design for Enhancing Durability

- Design gully outlets as an integral part of the floor slab.
- Monolithic in-situ or precast construction preferred.
- Regular maintenance of poorly performing gully outlets to remove debris and allow water to flow freely.

Identifying Potential Inadequacies/Inspection Information

- Note areas of ponding and any signs of related deterioration to surrounding areas.

Water ponding on roof due to incorrectly fitted drainage gully

Example of water ponding around the base of a column due to ineffective gully outlet.

References for Detailed Recommendations

1. “Design recommendations for multi-storey and underground car parks” IStructE report 3rd edition, 2002

1. “Recommendations for the inspection and maintenance of car park structures” ICE, 2002

Summary Sheet 6
Deterioration of waterproofing membranes/coatings

Brief Description

- Waterproofing membranes/coatings provide protection against water seepage into the structure, therefore protecting the concrete and any reinforcement.
- A poorly designed and/or installed membrane can degrade and reduce its ability to resist ingress of water, which may contain chloride.

Potential Effects on Durability & Structural Performance

- Failed coating allows water seepage through the structure
- Where water is trapped below the membrane, it can blister can become debonded due to heat from the sun. On bursting the membrane is breached allowing water ingress.
- Inadequate waterproofing membranes and poorly designed drainage results in ponding of water.
- Increased likelihood that reinforcement corrosion will have affected the structure
- Aesthetic concerns if the waterproofing is damaged.

Recommendations for Design for Enhancing Durability

- Consider the repair options available based on an adequate investigation and assessment of the problems observed
- Replace failed waterproofing with properly specified system ensuring crack bridging capabilities if required.

Identifying Potential Inadequacies/Inspection Information

- Carry out regular inspection of the membrane.
- Identify any areas of failed coating and determine reason for failure.
- Consider the repair options available based on an adequate investigation and assessment of the problems observed.
- If underlying concrete is cracked, check crack type (i.e. dormant/live) and replace with membrane with suitable crack bridging capabilities.
- Before applying coating check for frost damage and/or corrosion and structural significance of any deterioration.

Blistering and failure of waterproofing membrane

Typical example of failed membrane caused by its inability to bridge existing cracks in the underlying concrete.

References for Detailed Recommendations

1. "Design recommendations for multi-storey and underground car parks" IStructE report 3rd edition, 2002

1. "Recommendations for the inspection and maintenance of car park structures" ICE, 2002

Summary Sheet 7
Cracking and corrosion of deck slabs

Brief Description

- Substantial cracks can arise from flexural and from restraint effects leading to non-structural cracking.
- A common cause of large cracks in car park structures is due to thermal contraction/shrinkage.
- Uncontrolled flexural cracking has been observed in precast and in situ deck slabs, particularly “waffle”-type slabs and those with relatively thin cross-sections.
- Large shrinkage cracking can also form where slab depths are relatively thin.
- In “waffle”-type slabs cracking takes place not only in thin areas at the top of the slab but also transmits down the ribs and around the sides.

Potential Effects on Durability & Structural Performance

- Thermal contraction and shrinkage cracks generally pass through the entire thickness of the slab.
- Cracks >0.2mm are unlikely to self-heal and provide pathways for water and de-icing salts which leads to corrosion of reinforcement and spalling of concrete.
- Spalling of the soffit concrete is hazardous to users and can damage vehicles.
- Increased likelihood that reinforcement corrosion will have affected the structure

Recommendations for Design for Enhancing Durability

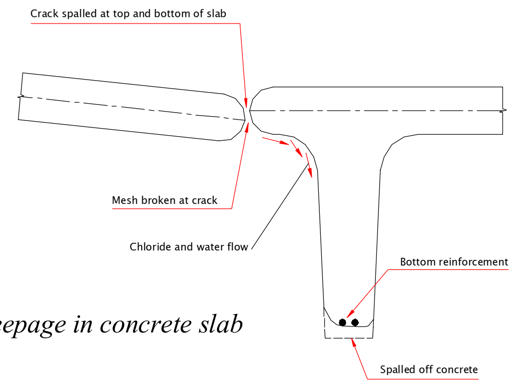
- Control of structural and non-structural cracking and robust design is essential for in situ deck slabs.
- Early sealing of large cracks (>0.2mm) and defects during construction will assist in reducing seepage through the slab and avoid long-term durability inadequacies.
- The use of suitably designed waterproofing membranes will also reduce the risk of seepage through slabs.

Identifying Potential Inadequacies/Inspection Information

- Undertake crack survey to the top and bottom of slabs to identify cracking type.
- Effective patch repairs difficult to undertake consider other repair techniques such as cathodic protection.

Patch repair of spalled concrete deck

Corrosion and spalling of rib of “waffle” slab



Cracking and seepage in concrete slab

References for Detailed Recommendations

1. “Design recommendations for multi-storey and underground car parks” IStructE report 3rd edition, 2002

1. “Recommendations for the inspection and maintenance of car park structures” ICE, 2002

1. “Non-structural cracking”, Concrete Society Technical Report 22, 3rd Edition, 1992

Summary Sheet 8
Typical problems: steel decks, pre-cast concrete and hollow core units

Brief Description

- Steel decks are prone to corrosion due to chloride-bearing de-icing salts.
- Corrosion of top flanges of steel beams and badly fitted column/beam connections.
- Precast concrete left in place formwork (e.g. "filgree units") supplied with less than 15mm cover to the bottom reinforcement.
- Corrugated asbestos formwork was also used historically and may still be present in some structures.
- Hollow core units fill up with water and crack when the water freezes.

Potential Effects on Durability & Structural Performance

- Corrosion of steel decks and top flanges of steel beams can lead to structural problems.
- Badly fitted steel column/beam connections can cause structural problems.
- "Fillgree" units with 15mm cover to bottom reinforcement corrode badly in service and are difficult to repair.
- Cores with hollow core precast units can fill up with water and crack when the water freezes. The depth of cover inside the core may also be inadequate, allowing salt-laden water to corrode reinforcement.
- Increased likelihood that reinforcement corrosion will have affected the structure

Recommendations for Design for Enhancing Durability

- Steel structures could be protected with a coating to improve resistance to corrosion.
- Water within hollow core units can be drained by forming holes in the soffit.

Identifying Potential Inadequacies/Inspection Information

- Top flanges of steel beams and steel column/beam connections are difficult to gain access to and so must be targeted during any inspection of a steel structure.
- Borroscope inspections required for hollow core precast units to identify hidden corrosion of reinforcement.

Corrosion of in-situ metal decking

Typical soffit spalling of precast concrete "fillgree units"

References for Detailed Recommendations

1. "Design recommendations for multi-storey and underground car parks" IStructE report 3rd edition, 2002

1. "Recommendations for the inspection and maintenance of car park structures" ICE, 2002

Summary Sheet 9
Common types of cracking

Brief Description

- Cracking of concrete is common in existing car parks and can accelerate deterioration processes by providing pathways for chloride-bearing solutions to pass to structurally sensitive areas of the structure.

Common Types of Cracking Found in Car Park Structures

- Critically stressed areas at column/deck connections and column head/beam zones.
- Expansion and contraction movements caused by thermal and/or moistures changes.
- Impact damage.
- Plastic, early thermal and shrinkage cracking due to poor site control and/or insufficient curing of concrete.
- Early removal of propping, particularly in cantilevered slabs.
- 'Hard spots' within the generally flexible structure.
- Construction joints and day joints which act as release points for stresses within the structure.
- Chloride- and/or carbonation-induced corrosion of reinforcement.
- Freeze/thaw damage.
- Alkali-silica reaction (ASR).

Typical example of leakage through shrinkage cracks in reinforced concrete deck slab

Typical example of radial cracking from around a column associated with flat slab.

Typical example of ASR-related cracking & damage.

Typical example of freeze-thaw damage & cracking.

References for Detailed Recommendations

1. "Design recommendations for multi-storey and underground car parks" IStructE report 3rd edition, 2002
1. "Recommendations for the inspection and maintenance of car park structures" ICE, 2002
1. "Non-structural cracking", Concrete Society Technical Report 22, 3rd Edition, 1992

Summary Sheet 10
Barrier fixings – holding down bolts

Brief Description

- Fixings for cantilevered barriers, fixed to the concrete deck, are particularly vulnerable to corrosion.
- Since most car parks are designed to fall towards the parapet, water often ponds around the parapet, and the base plates.
- Holdings down bolts, to the vehicle impact barriers, are therefore submerged for long periods.
- Many retro fit barriers are fixed through the waterproof membrane thereby puncturing the membrane and causing leakage around the bolts.
- Water tracks down the bolts and results in corrosion.

Potential Effects on Durability & Structural Performance

- Corrosion of holding down bolts
- Reduced fixing capacity
- Reduced bolt anchorage capacity
- Reduced resistance to combined tension and shear forces
- Lightweight waterproofing or asphalt on the base plate can cause differential movement leading to cracking.

Recommendations for Design for Enhancing Durability

- Design bolted connections at metal-metal contacts to BS 5950 or other appropriate standard
- Set base plates on plinths
- Use through-bolts with plate washers beneath
- Seal bolts into holes using high quality material
- Use stainless steel components
- Holding down bolt holes should avoid reinforcement
- Use diamond drilling for bolt holes
- Designers should take into account the ease with which bolts can be removed for inspection and possible replacement

Identifying Potential Inadequacies/Inspection Information

- Carry out hammer tapping survey of fixing holes
- Carry out detailed crack survey around fixing holes and base plates
- Note any signs of corrosion
- Note signs of water penetration and leakage, particularly on the soffit
- Carry out local breakouts in representative areas

Ponding of water around base plates and holding down bolts.

Corrosion of galvanised holding down bolts

References for Detailed Recommendations

1. "Design recommendations for multi-storey and underground car parks" IStructE report 3rd edition, 2002.

1. "Recommendations for the inspection and maintenance of car park structures" ICE, 2002

1. "Edge protection in multi-storey car parks – design specification and compliance testing", DETR Report, April 2001

1. "Guidance on the inspection of MSCP barrier systems", TRL Report, June 2000

Summary Sheet 11
Lack of cover in in-situ and pre-cast parapets

Brief Description

- In-situ parapets usually contain reinforcement, which is continuous with the slab, and this can often be quite robust due to the need of the parapet to withstand impact.
- Any deterioration of the rebars can compromise the ability of the parapet to contain errant vehicles.
- Parapets are generally designed down to a minimum thickness due to the need to minimise the weight at the edge of the structure, particularly if a cantilever design is utilised. Maximising the length of the parking bay is also an incentive to make such parapets as thin as possible.

Potential Effects on Durability & Structural Performance

- The combination of thin concrete structures and substantial reinforcement often leads to a situation of lack of cover to reinforcing steel and poorly compacted concrete.
- This increases the risk of chloride and carbonation-induced corrosion of rebars, leading to cracking and spalling of the concrete cover and potential loss of rebar cross-section and delamination of laps.
- There is also the potential for differential movement occurring between the horizontal and vertical elements of the parapet wall, which can be generally overcome by use of a small kicker. This may transfer the potential for cracking to the top of the kicker and in both cases care should be taken that such cracking is sealed by a water-resisting material.

Recommendations for Design for Enhancing Durability

- Where the potential for lack of cover may arise, care should be taken in the design and suitable protective materials should be utilised to provide additional protection if adequate cover cannot be created.
- Protective suitable materials include stainless steel reinforcement, protective coatings, such as anti-carbonation paint.

Identifying Potential Inadequacies/Inspection Information

- Where concrete parapets are formed on the edge of a cantilevered design, checks should be made to ensure that reinforcement is continuous through the deck slab.
- Careful visual inspection and testing of the bottom of parapet walls are required to check the condition of structurally sensitive reinforcement

Corroded reinforcement exposed by spalling of the internal face of a parapet.

Corrosion of reinforcement & cracking

References for Detailed Recommendations

1. "Design recommendations for multi-storey and underground car parks" IStructE report 3rd edition, 2002

1. "Recommendations for the inspection and maintenance of car park structures" ICE, 2002

Summary Sheet 12
Typical example of inspection and assessment of MSCP

Brief Description

- A reinforced concrete multi-storey car park (MSCP) approximately 17 years old, at time of testing
- Investigations carried out included removal of cores from the structure, half-cell potential survey and chloride content determination from powder samples
- MSCP being refurbished prior to transfer of ownership, requirement for remaining service life
- Repair options under consideration were electrochemical techniques (i.e. Cathodic Protection and Desalination)

Potential Effects on Durability & Structural Performance

- Initial casting conditions.
- Use of hot air blowers in cold conditions for casting concrete (an atypical example).
- Use of de-icing salts containing chloride
- High chloride levels throughout the depth profile that ranged from 1.4 to 6.1 % Cl^- by wt of cement
- Increased likelihood that reinforcement corrosion will have affected the structure
- Petrographic analysis indicating concrete characteristics.
- Cracks present on the concrete decks near the columns (not reported by previous inspections)

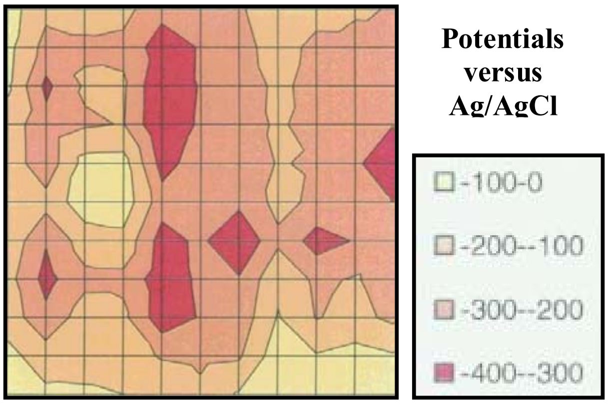
Recommendations for Enhancing Durability

- Ensure that the concrete casting conditions are suitable for production of durable concrete
- Consider application of alternative de-icing salts, on whole life costs
- Consider the repair options available based on an adequate investigation and assessment of the problems observed

Inspection Information

- When survey is carried out report where and when samples were removed.
- Improve presentation of half-cell potential information (i.e. Take iso-potential contour plots and map their location to the structure)
- Include cement content determinations in the chloride dust sampling programme (Note: petrography provides a better indication of cement content).
- Carry out local breakouts to confirm information obtained for cover and corrosion

Surface damage to concrete driving aisle
(Picture courtesy of BRE Limited)



Iso-potential map for parking bays
(Iso-potential plot courtesy of BRE Limited)

References for Detailed Recommendations

1. "Corrosion of Steel in Concrete: Part 2 Investigation and Assessment", BRE Digest 444

1. "Report 1 Review of NDT Survey Techniques" – Degradation of Materials in the Environment (DTI)

1. "Report 2 Handbook for Corrosion Rate Measurement " – Degradation of Materials in the Environment (DTI)

1. "Report 3 Corrosion Rate Measurement" - Degradation of Materials in the Environment (DTI)

Summary Sheet 13
Typical example of the application of cathodic protection systems

Brief Description
- Reinforcement in concrete can be subjected to chloride attack and carbonation caused by the environment in a car park.
- Cars track in de-icing salts containing chlorides from the road.
- Water seepage is also a common problem.
- A way to prevent these attacks degrading the properties of the reinforcement concrete is to apply a cathodic protection system, preferably before any damage starts to occur.

Potential Effects on Durability & Structural Performance
- De-icing salts containing chlorides migrate through the concrete and attack the steel reinforcement. Results are rusting of the rebar and eventually delamination and spalling of covering concrete.
- Carbon dioxide neutralises the concrete allowing the passive film on the surface of the steel to break down. Delaminations and spalling can occur as above.
- Water seepage through the structure promotes the corrosion of reinforcement. Rust staining is often observed.
- Increased likelihood that reinforcement corrosion will have affected the structure

Recommendations for Enhancing Durability
- After adequate investigation and strength assessment of the problems observed, a suitable cathodic protection (CP) system can be selected. This could be conductive paint, titanium mesh with cementitious overlay, conductive overlay, discrete anodes or a combination of several of these systems.
- Other methods may also be suitable for protecting the structure such as the use of inhibitors, electrochemical chloride extraction or electro-osmosis. However, many of these innovative methods require trials to evaluate their effectiveness and may not be suitable for structures with significant levels of chloride contamination.
- CP systems will give the longest lasting and most comprehensive protection in the right circumstances.
- Consultants/contractors with specialist knowledge of designing and installing CP systems should be consulted.

Inspection Information
- Carry out visual inspections of the structure
- Monitor the system at regular intervals (remotely or by

Large sections of soffit have spalled away due to rusting of the reinforcement beneath.

Rust staining resulting from corroding reinforcement caused by carbonation of concrete combined with the ingress of water.

Conductive overlay CP system on an area of soffit.

References for Detailed Recommendations

1. “Corrosion of Steel in Concrete: Part 2 Investigation and Assessment”, BRE Digest 444

1. “Report 2 Handbook for Corrosion Rate Measurement ” – Degradation of Materials in the Environment (DTI)

1. “Report 3 Corrosion Rate Measurement” - Degradation of Materials in the Environment (DTI)

3 Review of Inspection and Maintenance Approaches

Detailed guidelines for the inspection and maintenance management of car park structures are due to be published in December 2002 by the Institution of Civil Engineers[2]. The ICE guidance is a reaction to recent structural failures and accidents and concern about deterioration in the condition of many car park structures. As with the IStructE guidance[1], the PII project has provided information for the ICE.

For more detailed information on assessment, inspection, maintenance and remedial approaches to car park structures reference should be made to the ICE document[2]. The following provides supplementary information to the ICE document.

1. Prior to setting an inspection regime for a structure a combined structural and deterioration risk assessment should be considered, preferably utilising the skills of material and structural engineers. This should be based on detailed reinforcement drawings of the structure, with a realistic idea of as-built quality likely to have been achieved. This should identify structural critical parts and those which are sensitive to poor construction and/or deterioration. It also needs to identify areas where conditions of local exposure are likely to concentrate deterioration due to water ponding and seepage, carbonation, chlorides, frost, corrosion, traffic abrasion, etc. Particular attention in inspection should be focussed on those areas where aggravated deterioration combines with structural vulnerability. The assessment may indicate problems because of lack of detailed drawings and/or 'uninspectable' details which must be resolved by special investigation and testing.

2. An example of an 'uninspectable' detail is the corrosion of holding down bolts for edge protection systems. This is covered in Summary Sheet 9 and a schematic drawing of two types of 'uninspectable' bolts are shown in Figure 4.

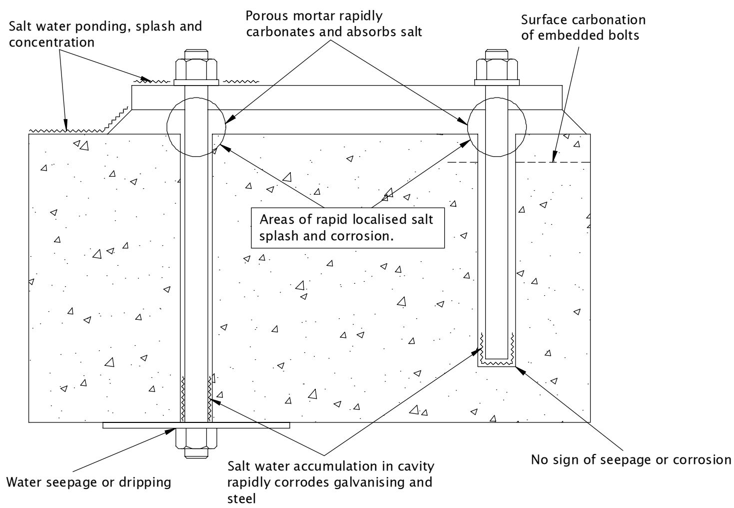


Figure 4 Schematic sketch showing two types of 'uninspectable' hold-down bolt.

3. It is important to have on record an assessment of the strength of the 'as built' structure or at least for a set of typical key elements including the barriers. This should check against current design standards, so that any weakness, lack of robustness or tendency to progressive collapse is identified. This assessment should consider the potential structural vulnerability of the details to deterioration and the risks of accelerated deterioration developing in the particular conditions in the car park structure due to frost action and/or corrosion. This is particularly important where details are not easily inspectable.

   Disproportionate collapse from an errant vehicle impacting a primary member should also be considered. Many of the early pre-cast and/or composite car parks would collapse if a slender column was removed. There are many examples of very slender columns which span clear over two storeys within the case studies reviewed for this project.

4. Assessment should check if the structure is robust, with a good resistance to progressive collapse, so that local deterioration does not trigger more widespread failures, which can lead to an extensive collapse. This robustness is now a requirement for structural design, but it was often not explicitly considered in design during the 1960s. Robustness makes a structure less susceptible to extensive damage from fire and explosions. Structures assembled from pre-cast elements with simple joints are often less robust than in-situ construction. It is important to identify if there are any features of the design, which might fail in a sudden brittle manner or develop into a collapse mechanism, either as built or after deterioration has weakened it.

5. Areas of low cover and ponding can be identified during construction and should be remedied during the maintenance period. Further areas of ponding may develop from creep deflections.

6. After a structure has been in service for 3 to 5 years the patterns of potential deterioration will have become established and can be analysed by selective sampling of sensitive areas to establish the trends of carbonation and chloride ingress, traffic wear, frost damage, water seepage, cracking, etc. and further ponding from creep deflections. From this, an initial estimate of future patterns of deterioration can be made to assist with planning inspections, maintenance work and long term budgeting. At this stage pre-emptive action can be taken to slow down deterioration by, for example, applying suitable coatings and preventing ponding of water. Construction defects discovered early can be referred to the contractor for remedial work.

7. It is not uncommon for ineffective superficial repairs to be carried out without a proper diagnosis of the underlying causes. Repairs and coating can then hide the more serious deterioration developing underneath.

8. The increasing knowledge of deterioration processes, and the development of methods of controlling deterioration rates by, for example, reducing moisture levels and/or cathodic protection enable deterioration to be slowed down and prolong the service life of the structure. The cost effectiveness and long term performance and reliability of these options need careful consideration for each structure and should be related to its condition and particular structural details. Improvements in drainage, waterproofing joint sealing and the use of anti-carbonation coatings need to be carried out as soon as potential problems are identified. If left till extensive deterioration is established they have a much reduced benefit.

9. Durability testing and monitoring of car park structures is a vital part of the inspection and assessment process. Guidelines on testing and monitoring the durability of concrete structures have been produced by the Concrete Bridge Development Group[17]

10. When coating, protection or repair is planned one must be absolutely clear about the objectives and aware of the strengths and weaknesses of the various products and procedures available. Purely cosmetic work may be of value in keeping the structure welcoming to the user, but will be unlikely to slow the underlying deterioration and may hide deterioration and make it uninspectable.

11. Waterproofing is an effective method of reducing moisture movement through concrete decks but attention to falls to prevent ponding is required to make it reliable.

[17] "Guide to testing and monitoring the durability of concrete structures", Concrete Bridge Development Group, Technical Guide 2, 2002

4 Review of Concrete Repairs

1. Repairs may be 'Non Structural' to patch a hole with no contribution to strength or corrosion control, 'Corrosion control' or 'Structural' where full restoration of strength and of corrosion control is essential. Repairs always require further cutting out to prepare the surface. A repair may also deteriorate and lose its structural effectiveness and consideration must be given to the possibility of corrosion developing around a spall.

2. Before repairs are started specialist structural engineering advice should be obtained to ensure that safety is maintained at all stages with an appraisal 'as built', 'as deteriorated', ' as cut out for repair', 'as repaired' and 'with repair delaminated'. From this an appropriate repair specification, with temporary support if necessary, can be developed.

3. It is difficult to make repairs structurally effective unless they are cut out deep enough to ensure that the repair is fully linked to the substrate concrete by the three-dimensional reinforcement cage. Provided the cause of failure is correctly diagnosed; the material to be repaired is fully tested and understood and the repair strengthening system, including additional steel reinforcement, is correctly specified, then structural repairs should be satisfactory. Generally full depth cutting out with high pressure water jetting and recasting with concrete of the similar properties to the concrete to be repaired is most effective. With part depth patches there are often problems of adhesion and delamination. The matching of stiffness, thermal and long term drying shrinkage properties to the substrate concrete is difficult to achieve with some high strength proprietary repair mortar products.

4. It is essential to ensure adequate propping whilst carrying out structural repairs in order to avoid over stressing the repaired section. The reason for and method of propping can only be determined after making a full assessment of the structural behaviour of the element under consideration – this may require reference to the original design or back analysing the existing structure where no calculations or drawings are available. Where the beam or slab under repair is continuous, the mid-span or cantilever should be propped before cutting out and exposing the support bars.

5. If a repair is to be effective in carrying load it will be necessary to prop the structure until the full strength and stiffness of the repair has developed. The load sharing between the repair and existing structure must be calculated taking into account the stress state when the repair has fully hardened and differential strains from long term shrinkage. In some instances 'belt and braces' remedial work, using additional external strengthening, will be more cost effective than cutting out and recasting the original poor detail, which can be left to harmlessly deteriorate. Through bolting of flat slabs between plates can prevent delamination of repairs and enhance punching shear strength.

6. If structural repair seems a daunting and expensive business it helps emphasise the need for better initial construction and early action to slow deterioration before structural damage occurs.

4.1 Field Studies of the Effectiveness of Concrete Repairs

Mott MacDonald Ltd., (MM) was commissioned by the Health and Safety Executive (HSE) in June 2000 to carry out a research study entitled "Field Studies of the Effectiveness of Concrete Repairs". The aim was to evaluate the effectiveness of the range of concrete repair systems as applied in practice, in order to improve procedures for maintaining the integrity of operational structures to achieve higher standards of structural safety and reliability and better whole-life management. It was intended to assess the processes by which repair is carried out and, in particular, identify the factors that lead to success or failure. It was not to compare the performance of similar materials, or products.

The project focused primarily, on non-structural patch repairs to reinforced concrete. Other types of repairs, such as crack sealing and CP, were included where present at the patch repair sites.

In total, 46 sites were visited including multi-storey car park structures. At certain sites more than one type, generation or condition of repair was present, consequently 65 different locations were examined.

The main recommendations/guidelines from the study [18] are given below.

4.1.1 Approach to repair

- The process of planning and executing repairs should be part of a structured approach to providing effective asset management. For each repair episode, there should be an owners 'statement of intent' which defines what is required of the structure in terms of future performance, service life and maintenance level.
- Before repair, the engineer should have a full and detailed understanding of the structure, its modes of deterioration, and likely future behaviour. A review should be undertaken to provide options for management of the structure to meet the 'statement of intent'. The review should consider practicality and cost, indicating the possible alternatives. The owner should be advised of the most appropriate strategy and the consequences of alternative strategies.
- Detailed inspection should provide a record of condition, to allow retrospective judgements to be made as to the effectiveness of the repair strategy and assist in evaluating future repair demand/intervals.
- The owner should be aware of, and implement, any maintenance and inspection actions required in the management strategy and review the results of these actions.

4.1.2 Repair activities

Specifications and method statements should be followed and repairs applied as intended. The works should be monitored full time and the records of site supervision retained. Particular attention should be given to:

a. selecting the limit of the areas to be repaired to minimise future corrosion potential,

b. checking break-outs have sawn edges and clean surfaces prior to reinstatement,

c. minimising the surface area of reinforcement exposed at the repair/substrate interface,

d. checking the coverage of any reinforcement primer,

e. checking the depth of break-out, thickness of layers applied and ensuring intersecting reinforcement is not present in layer interfaces,

f. checking the materials delivered and applied are in accordance with the specification,

g. ensuring curing practices and duration are in accordance with appropriate guidance, and

h. inspecting completed repairs and adjacent areas for evidence of deterioration, cracking, etc.

[18] "Field studies of the effectiveness of concrete repairs – Phase 4 Report", Mott MacDonald Report for the HSE (Ref. 56362/R1134/A). 10 August 2002

4.1.3 Records

- The owner should retain detailed records of condition, repair and maintenance. These should include details of the materials, and their specifications, used in repair and photographs and location references to enable comparisons of condition to be made in future. Records should be retained for the life of the structure, be updated regularly and be readily accessible, possibly in the form of a maintenance manual.
- The maintenance manual should also include the requirement for future inspection of condition and provide details of the locations and defects that should be given particular attention at the next assessment and repair phase.

4.1.4 Long-term protection

- For structures, which require an extended service life and are exposed to an aggressive saline environment or where there are hidden or critical details, consideration should be given to repairs and treatment of the whole structure using a high quality surface coating or a CP system. Durability modelling and whole-life costing can be used to assess the cost effectiveness of such an approach.

5 Recommendations for Enhancing Whole Life Performance

Recommendations for enhancing the durability of existing and future car park structures are provided and have been developed following a detailed review of real structures that have shown either good or bad performance.

- During the design of new car park structures the quality of design and detailing to ensure the car park drains properly is very important. Movement joints need to be considered when the overall form of the car park is evolved. They should be designed to ensure that they function structurally and are located in positions to avoid trapping water or leaking on to the deck below. The new IStructE recommendations[1] cover many of these points in detail.
- More robust and durable concrete than found in the case studies is possible through better detailing, the use of higher quality concretes and improvements in construction practice and supervision. This cannot be achieved by relying on traditional procedures covered in current building codes but should be based on the IStructE recommendations[1] that have been developed by taking into account durability requirements more akin to those for bridge decks or marine structures.
- The review of case studies has highlighted poor quality construction as a frequent source of inadequacies in the stock of UK car park structures. Construction defects can lead to substantial acceleration of deterioration processes. Proper priority should be given to quality control during construction. Areas of out of tolerance with the specified cover should be identified with a cover meter during the construction contract, not left hidden till they start to spall prematurely.
- Prior to setting an inspection regime for an existing structure a co-ordinated structural and deterioration risk assessment is needed, preferably utilising the combined skills of material and structural engineers. This should be based on an inspection of the detailed reinforcement drawings, with a realistic idea of as-built quality likely to be achieved based on inspection of the structure. Particular attention in the inspection should be focussed on those areas where aggravated deterioration combines with structural vulnerability. The assessment may indicate problems because of lack of detailed drawings and/or 'uninspectable' details which must be resolved by special investigation and testing.
- Owners should develop a long-term strategy for maintenance of their existing car park structures and barriers working with structural engineers and materials specialists to define and implement a Life-Care Plan that includes:

  (a) Identify the key areas of structural weakness and/or structural sensitivity to deterioration.

  (b) Establish current trends of deterioration and predict long term trends by targeted investigation.

  (c) Draw up check lists for regular inspections based on a) above.

  (d) Identify where and when preventative protection, strengthening or repair is, or may become appropriate.

  (e) Fully record all condition surveys, modifications and repairs.

  (f) Ensure the condition of concrete and reinforcement and their structural effectiveness are checked and recorded before they are hidden under coatings and repairs.

  (g) Ensure good falls, wash down regularly and keep the drains clear.

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Appendix A: Analysis of Case Histories

A.1 Background

A total of 203 case studies have been reviewed, spanning a range of structure types built over the last 50 years. There are approximately 4,500 multi-storey car park (MSCP) structures in the UK so the sample collected represents approximately 4.5% of the total UK MSCP stock.

Figure A1 shows a histogram of the dates of construction of the car park structures examined during the project. The age of the structures tested is shown in *Figure A2*. It is clear from these Figures that the majority of case studies of deteriorating car park structures related to those built in the 1960's and early 1970's. This reflects the boom in MSCP construction during the period and inadequate (in hindsight) lack of technical guidance on structural design, exposure conditions, durability design and generally poor workmanship prevalent at the time.

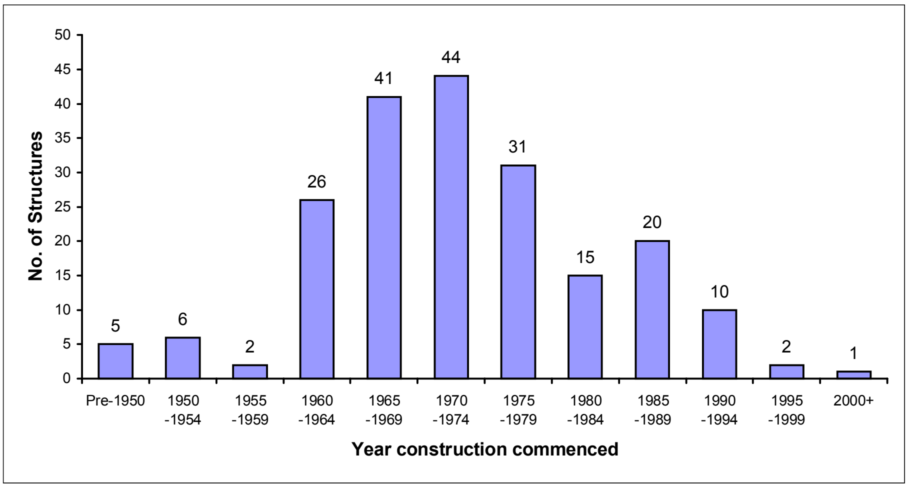

Figure A.1 Dates of construction of car park structure case studies

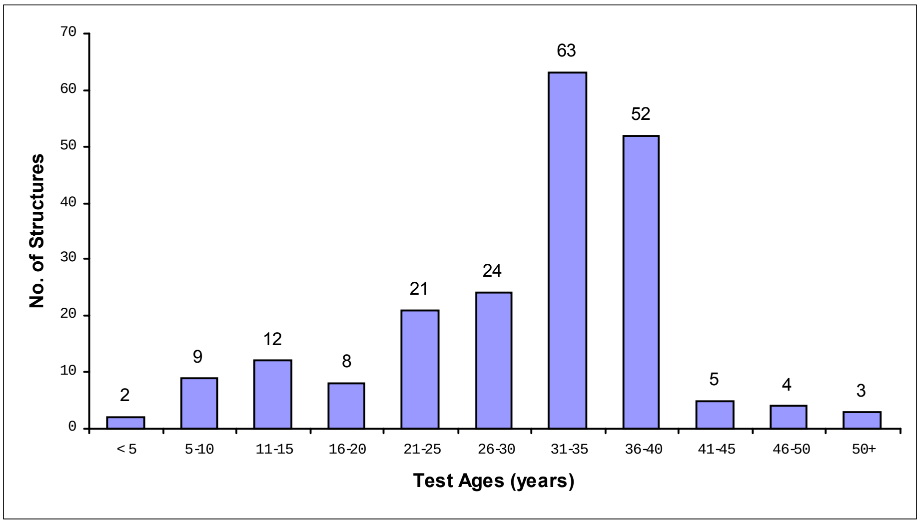

Figure A.2 Age of structures at date of testing/investigation

A.2 Structure Types

The case studies reviewed for this project were all multi-storey car parks (MSCP). The overwhelming majority were concrete frame structures comprising 59% in-situ concrete and 38% pre-cast concrete. The number of steel frame structures reviewed was only 6 (3%).

Due to the variety of car park designs, often combining a range of structural forms, it is not possible place the case studies into distinct categories. Instead the principal structural components that make up the car park structure (i.e. beams, slabs and parapets) were categorised into generic types. The population of each type is shown in *Figures A3 to A5*.

Based on this listing, a subjective list of the main types of car park structures reviewed includes the following categories:

1. In-situ reinforced concrete frame and slab.
2. In-situ frame, pre-cast pre-stressed deck.
3. Pre-cast frame and deck (including lift slab construction).
4. Steel structure with pre-cast floors.
5. Structural steel deck with in-situ, or composite deck.
6. In-situ concrete with bonded post-tensioning.

A.3 Reasons for Investigations

The case studies reviewed are based on the reports of condition surveys and/or investigations carried out due to concerns over structural safety or serviceability and usually prior to replacement or refurbishment. Many studies were initiated because of visible signs of deterioration within the structure. The most common of these shown below:

- Ponding of water
- Leaking joints
- Deterioration of joints
- Leaking roof
- Inadequate edge barrier protection
- Corrosion of reinforcement
- Corrosion of structural steelwork
- Spalling of concrete
- Cracking of concrete
- Worn surfacing/deck slab
- Deterioration of waterproofing membrane

It is also worth noting that approximately 52% of the car park structures were found to have concrete contaminated by cast-in chlorides. These originate mainly from admixtures containing chlorides (e.g. calcium chloride accelerators) used up to the early 1970s but there were also several examples of chloride contaminated aggregates being used during construction.

Photograph 21 Typical example of in-situ reinforced concrete frame and slab structure

Photograph 22 Typical example of concrete frame structure

Photograph 23 Typical example of steel deck structure

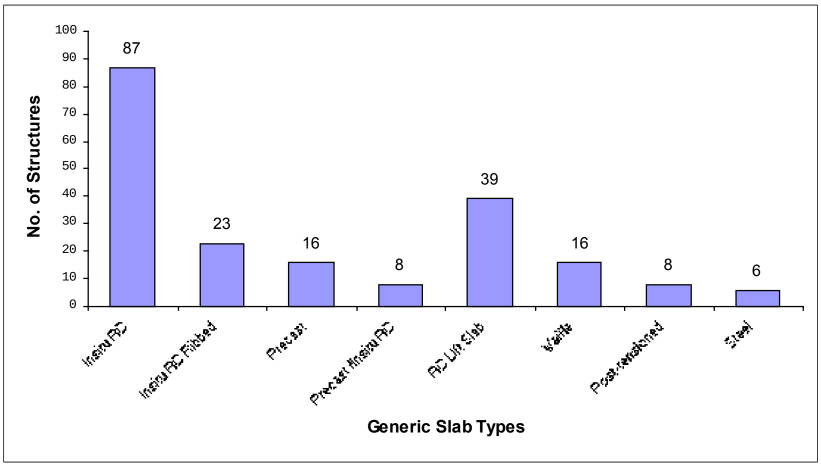

Figure A.3 Generic slab types

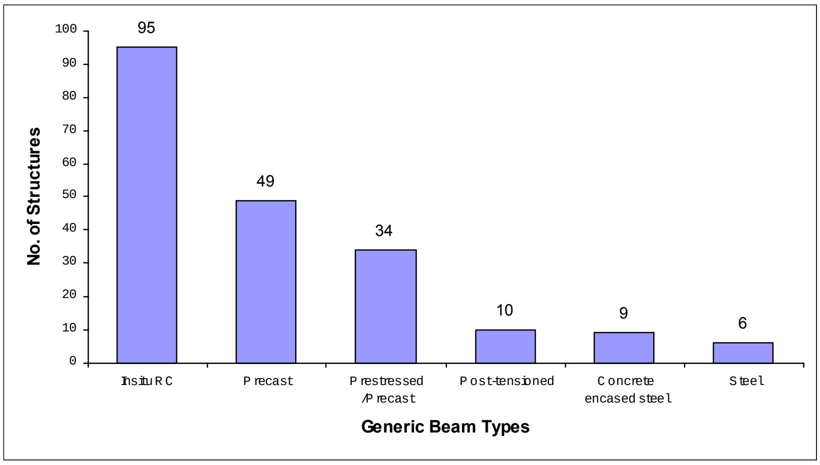

Figure A.4 Generic beam types

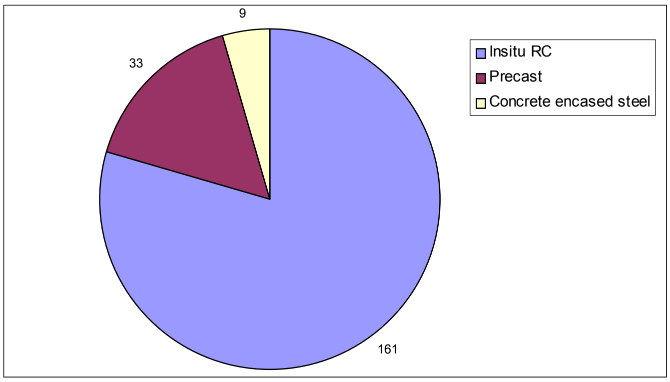

Figure A.5 Generic parapet types