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EDGE PROTECTION IN MULTI-STOREY CAR PARKS

- Design Specification and Compliance Testing

Final Report

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Contents

1. INTRODUCTION

The concern over the inadequacy of vehicle edge protection in multi-storey car parks stems from a series of accidents in recent years, including some in which errant vehicles have breached the vehicle restraints and plunged to the ground. There is considerable potential for such cars, or parts of the vehicle restraints, or sections of dislodged cladding, to cause injury to pedestrians in a crowded city centre below.

There was no specific guidance available to designers prior to 1972 to help them provide edge protection to an adequate and consistent standard. Consequently, approximately 25% of the car park stock was constructed without reference to any national design standard for edge protection.

Current standards quantify a design impact, but provide no precise test method by which to judge compliance. The standards have been interpreted in a variety of ways, which meant there has been inconsistent quality of edge protection installed in new car parks. The testing of existing installations for adequacy has been made to widely differing safety levels.

Industry lobbying and concern expressed by the Standing Committee on Structural Safety (SCOSS)[1] led the Department for the Environment Transport and the Regions to commission a Partners in Innovation project led by Southampton University (and completed at the Royal Military College of Science, Cranfield University) and assisted by TRL Limited. The work was guided by a Steering Group which included other partners from industry (see Acknowledgements). The overall objective of the research was to provide a basis for the reduction of the risks of death and injury occurring in car parks. Risk reduction is sought for accidents involving impact of vehicles with the edge protection (both on elevated floors and on access ramps), and due to pedestrians falling over, under, or through those edge restraints.

The study set out to achieve the overall objective by delivering five clearly identifiable outputs, namely:

1. Production of a **Design Specification and Compliance Testing** document, reconciling the disparate requirements of existing standards and codes through necessary revisions.
2. Definition of an **Assessment Method for Installed Vehicle Restraints** covering the majority of existing installations, based on a visual inspection and desktop calculations using data for common edge protection systems obtained from laboratory tests.
3. Specification of on-site test equipment and procedures to determine the adequacy of any novel or non-standard installation not covered by the foregoing **Assessment Method for Installed Vehicle Restraints**.
4. Publication of design, detailing and inspection guidance to describe recommended best practice, unacceptable practice, and giving sample calculations for local installation details. This guidance has been included in the two aforementioned documents.
5. Publicity and dissemination of the **Design Specification and Compliance Testing** and the **Assessment Method for Installed Vehicle restraints** documents.

This report describes the design specification, its development and the supporting test programme, and the resulting vehicle restraint compliance test procedures. It is based partly on TRL Limited's contribution to the project, contained in their report "Literature Review of Multi Storey Car Park Edge Protection Vehicle restraints"[2], the experimental vehicle restraint test programme, contributions from Project Partners, and the discussions and agreements reached by the Steering Group.

The participation of the key industrial suppliers and installers of car park edge protection vehicle restraints has led to a rapid implementation of the research output, even during the period of the Project contract.

2. BACKGROUND

2.1. Edge Protection Systems for Restraining Vehicles.

There are three principle types of edge restraint:

- those that span between primary structural members (commonly horizontally between the columns),
- those that cantilever up from the car park deck, and
- those that are monolithic with the deck.

Choice of type for installation depends upon many factors, such as the type of structural frame, deck construction, space available, and required ease of replacement.

The first type consists of cold-rolled, or for longer spans hot-rolled, steel sections that absorb the vehicle energy by yield mechanisms. Recently, wire systems have also been proposed. Fibre composite systems that absorb energy by fracture mechanisms are also potentially suitable to span between structural frame.

The second type consists of cold-formed section rails supported on either cold-formed posts or hot-rolled steel posts. The most common rail is the standard section motorway vehicle restraint, with open-box beams of trapezoidal section and sigma section also used. The posts can be subdivided into three further categories of stiff, fully welded construction of post with its base; intermediate stiffness posts incorporating a rubber energy-absorbing buffer between the post and its base, and flexible posts of curved spring steel construction

The third type is of monolithic concrete construction with continuity reinforcement between the wall and floor deck. The majority of load is carried by cantilever action, though in some cases the vehicle restraint acts as a three-side supported slab. The relative rigidity and greater mass of this type of vehicle restraint means that it relies on the momentum at impact being distributed throughout much of the car park structure and energy being absorbed by elastic strain energy.

2.2. Historical Introduction

Estimates of the number of UK Multi-Storey Car Parks (MSCPs) range between 4000 and 5000. This is about a quarter of the number in the USA, despite seven times as many vehicles being on the road there. It is also believed to be the highest number per capita in Europe. This high concentration of multi-storey car parks reflects the historical development of British cities, characterised by urban private housing, in contrast to the more common European development of more centralised rented apartments.

Early Multi-Storey Car Parks were generally designed and built to the lowest cost per parking bay. As a consequence the edge protection exhibited various defects during use due to inadequate design, poor detailing and structural deterioration. Many early perimeter vehicle restraints were inadequate for the purpose for which they were intended. Examples of inappropriate installations have included unreinforced masonry, 100 x 50 softwood rails, and wired glass panels.

The first attempt to quantify the impact loading of an errant vehicle on an edge restraint system was in 1972, as a supplement to the British Standard Code of Practice: CP3: Chapter V 1967: Loading: Part 1: Dead and Imposed Loads.[3]

The relevant clause in the Code of Practice required a perimeter vehicle restraint effectively to contain a 1500 kg car, travelling at 10 mph, impacting normal to the vehicle restraint. It also provided designers with means of calculating an equivalent static force that a vehicle restraint was required to withstand.

Car park owners and operators have a responsibility to ensure their premises are reasonably safe for use by lawful visitors under The Occupiers Liability Act of 1957. However, they are under no obligation to carry out inspections at regular intervals to ensure public safety and local authorities are powerless to intervene under the Building Act 1984 unless buildings are in a dangerous or obviously defective state. There are also provisions under the Health and Safety at Work Act 1974 requiring an employer to conduct his undertaking in such a way as to ensure so far as is reasonably practicable that persons not in his employment are not thereby exposed to risks to their health and safety.

2.3. International Standards

The European Standard dealing with MSCP edge restraint systems is DD EN 1991: Eurocode 1: Basis of Design and Actions on Structures[4]. It consists of 10 parts, which have only been accepted to date for publication as ENV prestandards for voluntary experimental use. Annex C of prENV 1991: Part 1.1: Densities, Self-Weight and Imposed Loads in Buildings deals with "Vehicle Restraints For Car Parks". The prENV 1991 Standard's National Application Document adopts the current UK standards, BS6399: Part 1 and BS6180[5,6].

ENV 1991-2-7 November 1998: Eurocode 1: Basis of Design and Actions on Structures - Part 2-7: Actions on Structures - Accidental Actions due to Impact and Explosions[7] provides values of impact forces that columns must be capable of withstanding when struck by vehicles on adjoining highways. The values given in ENV 1991-2-7 are due to become mandatory after November 2001. The current sources for this information in the UK are the Design Manual for Roads and Bridges[8] (particularly sections BD 37/88, BD 52/93, and BD 60/94), BS5400: [9] and BS6779: Part 1: 1998[10].

The German standard, DIN 1055: Horizontal Impacts on Non-Load-Carrying Boundary Structures[11], and the Dutch standard NEN 6702: Loads and Deformations[12], require an impact equivalent to a maximum static load of 90 kN. The Belgian[13] and Swiss[14] requirements are for static loads, taking no account of vehicle restraint deformation, of 100 kN and 50 kN, respectively. The UK requirements are the most demanding, requiring an impact equivalent to a maximum static load of 150 kN.

In the United States of America, the generally accepted standard is that of the American Parking Consultants Council of the National Parking Association (NPA). This standard recommends a single static load, of 45.45 kN spread over a square area of side 0.305 m, 0.457 m above deck level. The American Concrete Institute's 1994 Guide For The Design of Durable Parking Structures[15] indicates that some individual States have special requirements, notably Texas (Houston) and South Florida. These requirements in some cases are more onerous on flexible vehicle restraint systems, but are less onerous on rigid vehicle restraint systems.

2.4. The Current UK Standards for Car Park Edge Protection

The current UK design standards, BS6399: Part 1 and BS6180, use the same basic requirement for perimeter vehicle restraints of MSCPs. For car park decks designed to carry vehicles whose gross mass does not exceed 2500 kg, the vehicle restraints should contain effectively a single impact from a 1500 kg car, travelling at 16 kph (which approximately equals 4.5 m/s or 10 mph), impacting normal to the vehicle restraint. The standards provide designers with a means of establishing an equivalent static force to be resisted by the vehicle restraint. This force should act normal to the vehicle restraint, at a height of 375 mm above floor level, and be uniformly distributed over any 1.5 m length of vehicle restraint. Its magnitude in kN is calculated from the following equation

$$F = 0.5\ m\ v^2 / (d_c + d_b)$$

where
- m = design vehicle impact mass (usually 1500 kg)
- v = impact velocity (4.5 m/s)
- d_c = vehicle distortion (generally taken as 100 mm)
- d_b = vehicle restraint distortion in mm

In the event of such an impact, the expectation is that the vehicle restraint will need to be replaced.

The present standards specify that, on ramps, allowance may be made for the difficulty with which a vehicle can impact normal to the vehicle restraint. The design static force is halved. However, at the approaches to the ramps, the change of gradient combined with the bonnet (or boot) overhang can cause the specified bumper height to increase. The impact height specified for the ramp is the 610 mm used for highway vehicle restraints. This 610 mm height represents the impact from a vehicle wing at an angle, which is higher than impact from a bumper.

Opposite long straight ramps, the potential for increased impact speed is recognised by the requirement for double the design static force. Again, the impact is specified at 610 mm high. The reason for this increased height is that if the vehicle restraint is located shortly after the ramp finishes, then the vehicle may bounce on its suspension. Impact is not necessarily inclined in this situation.

There are no specific requirements at any other locations, so vehicle restraints are assumed to be not required (walled up stair wells are sometimes not considered as an edge of the deck) or not required to the standard generally applicable to the deck edge (e.g. between split level decks).

3. REVIEW OF THE UK DESIGN STANDARDS.

One purpose of the research described in this report was to eliminate ambiguities that had been identified in the existing Standards. Consequently, all relevant aspects of the current specifications, BS6399, BS6180 and Approved Document K of the Building Regulations, were critically reviewed by the Project Partners. The outcome of this review is summarised below.

The first consideration was the functional purpose of the edge protection. The purpose is clearly to restrain errant vehicles, but also it is to protect pedestrians from falling off the deck. Thus the edge protection for car parks fulfils two primary safety functions: -

- As a vehicle edge restraint
- As a safety restraint for pedestrians and particularly children

In its capacity as a vehicle edge restraint, the edge protection should confine an errant vehicle within the structure. Car parks are usually constructed in city centres. Most are adjacent to busy roads or public access areas such as shopping precincts, with extensive pedestrian access around the outside of the structure. In the event of a vehicle breaching the edge protection, there would be a significant risk of multiple injuries amongst passers-by as well as amongst the vehicle occupants. The requirements for the containment of the errant vehicle must also include the constraint that, during an impact, the cladding of the car park structure should not become dislodged and fall. SCOSS considered that vehicle edge restraints were inadequate in situations within many car parks where long access routes permit development of higher speeds than normal. Many existing fastenings for vehicle restraint support posts that are surface-fixed to the main structural members also may be inadequate.

Some multi-storey car park edge protection installations have failed to contain vehicle impacts. There have been several instances, such as that which occurred at Canterbury in January, 1996, where an edge restraint installation failed under impact allowing a car to pass over the edge of the car park, and fall to the ground below, injuring the occupants. One Partner in this Partners in Innovation Project has estimated that his firm makes 70 inspections per year of existing installations after impact incidents. Consequent replacements provide up to 40% of his firm's workload. These replacements are frequently for complete installations on the structure as a whole after assessment of the existing installation has shown it to be inadequate. These incidents are often "hit-and-run", and are not separately identifiable when reported as motor insurance claims.

It is recognised that a determined attempt by a driver to break out of the confines of the car park cannot be restrained. Indeed, it is essential to limit the energy imparted to the structure by an errant vehicle impact to avoid excessive damage to the structure itself. Columns are particularly vulnerable in this respect, with progressive collapse of the structure a possibility in some cases.

Part of the reason for the current lack of compliance of vehicle restraints with existing standards is an absence of clear and detailed guidance on what is required, and a method of assessment of installations and proposed installations for conformity.

The current specifications for design of edge vehicle restraints within car parks subjected to impact of vehicles do not take account of:

- the possibility of greater speed of impact with increasing size of car parks
- the results of proof tests since no proof test specification is available.

Disparity of provision also results from different interpretation and application of the current requirements in BS6399. Test reports in circulation suggest that some of the following parameters have been chosen to align with BS6399 requirements: -

- the crumple zone shear characteristics, or
- mass, or
- velocity, or
- momentum, or
- impact energy.

However, each choice of constant parameter will produce a different test result. Some of the tests will be more onerous than others, depending on the choice of parameter.

Accidents to pedestrians occur due to inadequate balustrades in car parks. It has been estimated from a student's study of south coast car parks that, if vehicle restraints consisting of solid cantilevered concrete upstand walls are excluded, close to 70% of the remaining car park edge protection vehicle restraints do not comply with all existing design and safety standards. Most of these instances result from inadequate protection for pedestrians. The Standing Committee of Structural Safety has identified child safety as a particular concern in many existing car parks. Standards for balustrades from BS6399 and the Building Regulations Approved Document K, have been adopted by many designers as being generally appropriate.

3.1. Factors Relating To The Standard Vehicle Edge Restraint Specification

3.1.1. Vehicle Mass. Improved material utilisation in car production has led to a general reduction in like-for-like vehicle mass. However, there is still a significant market in larger saloon cars. Payloads have also increased, with roof racks and roof boxes adding to vehicle manufacturers' gross laden weights.

The increased use of 4-wheel drive vehicles and multi-purpose vehicles has added to the top end of the mass distribution amongst the vehicle population. A small proportion (possibly about 1%) of vehicles capable of accessing car parks is known to exceed 2500 kg when fully laden. If the proportion of vehicles with mass exceeding 2500 kg becomes significant, then their access to multi-storey car parks may need to be restricted. European Standards are already proposing a higher 30 kN maximum passenger car weight, yet with a lower 20 kN vertical design load, but have not at present proposed a horizontal design load for car park edge protection.

The upper characteristic value of the vehicle mass distribution is considered to have remained virtually unchanged over the last two decades. The reduction in BS6399 from 2500 kg to 1500 kg for impact calculations is based on use of a statistically more likely laden vehicle mass.

There is no proposed change of the 2500 kg design vehicle for vertical loading, or the corresponding 1500 kg mass for horizontal impact loading.

3.1.2. Impact Velocity. Speed restrictions in many car parks are set at 5 mph (8 kph), since, of necessity, the traffic and pedestrians are sharing deck space. Car bumpers are designed to limit damage to pedestrians at 5 mph[16]. The design speed of impact on vehicle restraints is double this figure, because vehicles cannot be relied on to keep within the posted speed limit, particularly where pedestrians are not visible. Indeed, if the limit were adhered to, considerable car park access congestion would result.

Conversely, a vehicle restraint designed to restrain a high-speed vehicle would introduce a greater risk of damage to the car park's structural frame. For example, columns may be distorted and thereby their susceptibility to buckling increased.

The possible consequence of overall structural failure and collapse militates against raising the present design impact velocity.

No change to the 16 km/h impact velocity is proposed.

3.1.3. Impact Width. Introduction of side impact protection to car doors has caused vehicle widths to increase. Indeed, many clients now demand a 2.5 m minimum bay width rather than the traditional minimum of 2.4 m. (2.3 m is sometimes accepted where parking bays are allocated for repeated use, e.g. to employees, who will tend to be single vehicle occupants and take greater care of their own and colleagues' cars than the average motorist.) Even wider bays are specified for the disabled, and mother-and-toddler shopping. However, bumpers and wings are increasingly rounded, and form part of car body crumple zones, so the width of impact remains little changed.

No change is proposed to the 1.5 m impact width.

3.1.4. Impact Height. Since the current standards adopted a 375 mm height of vehicle restraint above floor level, the height of car bumpers on new cars has become more uniform so they make contact at 445 mm height. The mean height of the bumper centreline in a recent TRL Limited survey was very close to this 445 mm, and nearly 20% higher than the currently specified value. TRL Limited has proposed[2] that the impact height should be raised to 445 mm. This proposal results in a more onerous requirement for vehicle restraints that are cantilevered from the deck. There is compensating effect in vehicle restraint behaviour, however, arising from increased material strengths at high strain rates. Recent tests show that this change does not adversely affect installations using current proprietary designs.

Adoption of an impact height of 445 mm, raised from 375 mm, is therefore proposed.

3.1.5. Centroid Position. The use of lightweight body shells and increased use of plastics have lowered the centroid of vehicles. This trend is advantageous in the event of impact with MSCP edge protection. TRL has measured the centroid position for cars and it lies in the range 530 ± 50 mm, though it is significantly higher for off-road vehicles. However, the important factor is the height of impact, because the vehicle's suspension will absorb much of the moment created by the offset of the centroid from the impact height.

It is proposed that a horizontal impact at 445 mm height quoted in 3.1.4 be used to define the design impact.

3.1.6. Vehicle Deformation. There is an interaction between the flexibility of the vehicle and of the edge restraint, but without extensive additional research this is unquantifiable. There may be a case for increasing the scope of ISO 2958: Road Vehicles - Exterior Protection For Passenger Cars[16], as there is at present no correspondence between the impact design expectations of vehicles and of the structures against which they may impact.

Vehicle deformation on impacting a vehicle restraint will vary depending upon make, age, condition, and exact angle of contact, as well as on the vehicle restraint flexibility and impact position. It is probable that crumple zones will permit greater deformation of most modern vehicle bodies, but it is also likely that more densely packed engine compartments, or the use of bull-bars for example, will reduce the deformation and thus tend to create greater impact forces. To measure a representative number of real impact deformations would be very expensive.

The present assumption of 100 mm appears to be realistic for pseudo-static loading. No change is proposed to this value.

3.1.7 Strain-Rate Dependent Material Behaviour. The distribution of stress and effective plastic bending moment as the vehicle restraint decelerates the impacting mass are very difficult to predict with accuracy. If a dynamic impact test is scaled by a linear geometric factor, s, then the scaling of other factors should be in proportion to their units of measurement if all the full-scale properties are to be directly represented by the model.

Not all scaling factors can be maintained in the requisite proportions at anything except full scale. Hence none of the test methods previously conducted, as interpretations of the requirements of BS6399, truly represent the conditions currently specified. Strain rate dependent material behaviour, particularly, has hitherto been ignored in car park edge protection tests.

The strain rate in bending at the instant of impact is a function of the impact velocity, the section depth, the impact width and the span. The dynamic flow stress (equivalent to the yield stress in static structural design) can be estimated for each case from the Cowper & Symonds[17] constitutive equation. The resulting values lie between 2.1 and 1.9 times the yield stress. The magnitude of these results indicates that ignoring strain-rate dependent material behaviour introduces significant errors into the simulation of impact tests by pseudo-static tests.

Adoption of a full-scale dynamic compliance test is proposed for each edge protection system to prove it is able to resist the high dynamic flow stresses.

3.2. Non-Standard Vehicle Edge Restraint Specifications

3.2.1. Ramp Edge Protection. The current ramp edge protection in BS6399 requires half the design force to be applied at 610 mm above the ramp level.

The ramp edge protection requirement accords with the highway safety fence requirement, and is adequate.

3.2.2. Stair Well Edge Protection. The risk to pedestrians within stairwells of vehicles or dislodged masonry falling onto them is as great as at the edge of car park decks.

The same requirements should apply to stair well edge protection as at the edge of the deck.

3.2.3. Long Access Lane End Protection. When a vehicle's approach length to any vehicle restraint exceeds 20 m in a straight line (at the ends of decks or the ends of ramps), then it is proposed that greater edge protection be provided. Two options are proposed. Either traffic calming measures should be installed to restrict the vehicle to the specified velocity, or the vehicle restraint and its primary structure support should be designed to withstand an enhanced force. This enhanced design force is proposed to be twice the calculated static force, acting at the new standard impact height of 445 mm (see Section 5).

In the absence of traffic calming measures, all edge protection with greater than 20 m approach length should be designed for twice the static design force applied at 445 mm height.

3.2.4. Split Level Deck Edge Protection. The provision at split level deck edges should be the same as at other edges. However, the deflection criteria proposed in Section 5 and given in tables 2 a-f may be relaxed, provided designated pedestrian routes do not pass immediately next to the lower deck edge beneath these vehicle restraints.

There is scope for relaxation of deflection criteria at split level deck boundaries.

3.3. Pedestrian Edge Restraint Specification

The Building Regulations Approved Documents A, D and K, BS6399 and BS6180 give requirements for pedestrian guard panels and balustrades. The edge protection should restrain pedestrians, including children, from accidentally endangering themselves. The provision should therefore be similar to that of other balustrades, the requirements for which may be summarised as: -

- providing adequate strength, which may be justified by calculation or by tests similar to the Installation Compliance Test, but using the reduced loads of 1.5 kN/m on the balustrade handrail, 1.5 kN/m^2 on the balustrade area, or 1.5 kN at any point location,
- resistance to the through passage of a 100 mm diameter ball, and
- adequate height to restrain children, even if they are climbing on the vehicle restraint system (1.1 m above the highest foothold).

The attraction of vehicle restraints and posts for climbing by pedestrians, and especially children, should be taken into account. Hence, where the vehicle restraint is located inside the pedestrian guard and the rail or posts provide accessible step footholds, the balustrade height should be measured from the highest foothold.

Combined vehicle and pedestrian restraints, or dual systems (where a second restraint is installed in front of a pre-existing one), must demonstrate an equivalent performance to that required separately for each function.

Balustrades in staircase areas inaccessible to vehicles may be designed to the appropriate lower intensity of balustrade loadings in the Approved Documents and British Standards.

Pedestrian edge restraints should be provided to a height of 1.1 m <u>measured above the highest foothold reached by a rise of less than 550 mm</u>.

Provided pedestrians are directed not to use the vehicle ramps, the pedestrian guard may be omitted on internal edges of ramps where the drop to the adjoining deck is less than 600 mm.

4. PROPOSED COMPLIANCE TESTS.

4.1 The Need for Compliance Tests.

Estimates for some of the test data from this study indicate impact strain rates varying between 0.10 per second and 0.62 per second. Static formulae calculations predicted that the ratio of the deflection of the 10 metre span vehicle restraint reported in Table 2b to that of the 7.5 metre span vehicle restraint would be 1.8:1. The measured deflections were actually in the ratio of 1.24:1. These results alone indicate that strain-rate dependence of the material properties is significant in these tests.

Consequently, it is proposed that there should be two tests. The first is a full-scale dynamic test used to verify the compliance of a particular design of vehicle restraint system. It is envisaged that the dynamic test will normally be undertaken as part of a vehicle restraint system's development. The second is a pseudo-static test used to verify the adequacy of an installation of the vehicle restraint system at a specific location. Pseudo-static tests may be undertaken on completion of or during a trial installation on site, during fixing trials by a supplier, or to test the adequacy of fixings where the system may have deteriorated in use, i.e. in-service evaluation.

Not all installations need be tested. The dynamic test will only be required for a novel edge protection system, and the pseudo-static test will only be required when the quality of supporting materials, system materials, or installation are suspect.

4.2. Compliance Test for a System.

Initially, a series of full-scale dynamic proof tests of a vehicle restraint system should be used to establish compliance of the vehicle restraint system. These tests are to establish the suitability of interacting component stiffnesses, inertia, and strain-rate dependent properties. The tests should maintain at full scale the geometry, the mass and the input energy implicit in the specified impact. Thus the mass must be 1500 kg, with its centroid acting 445 mm high over 1.5 m width, and travelling at 16 km/h on impact.

At least one test should be carried out at each of the following positions: -

- at the rail midspan (to apply greatest impact to the rail),
- centred around an intermediate supporting post (to apply greatest impact to a single post), and
- at the nearest possible position to the end of a vehicle restraint at the corner of the deck.

To simulate the vehicle's ability to crumple, with the differing rigidity between the wings and drive mechanism, the proposed test subdivides the impacting mass into 30 separate rigid steel masses of 50 kg (or near equivalent). With no shear transfer between adjoining masses at the time of impact, this arrangement allows the impacting mass to conform to the vehicle restraint's developing deflected shape. The masses should present a vertical face to the vehicle restraint at impact, and there should be no significant loss of energy as the vehicle restraint deflects.

A view of a suitable test apparatus, primed ready for the loads to be released, is shown in Figure 1.

4.3. Compliance Test for an Installation.

An alternative test to the System Compliance Test is desirable for use on existing car park installations. A pseudo-static test is easier to implement, safer during execution, and consequently cheaper. The following Installation Compliance Test is therefore proposed for use to:

- select suitable fixings of the edge protection system to the structure
- settle disputes over the quality of installation of new systems
- assess the adequacy of existing installations in suspect areas identified during structural inspections

Specific fixing arrangements can be tested in-situ using the following pseudo-static test. It is proposed that these tests comprise three matching horizontal actuators (jacks) spaced 0.5 m apart, and fed by a single hydraulic source. Each actuator should apply its load through a swivel ball seat against a 400 mm long by 50 mm wide hardwood timber spreader along the vehicle restraint beam, at the specified height of 445 mm. (This position may be unstable for some barrier beam geometries. In such cases methods should be devised to apply equivalent bending moments to each component.) Any connection between the timber spreaders must have a bending stiffness less than 5% of the vehicle restraint beam bending stiffness. Guides must be provided to maintain correct alignment of the forces onto the back of the spreaders as the vehicle restraint beam distorts.

Figure 1. A suitable dynamic proof test apparatus.

The tested edge restraints should resist the static force for the specified impact. This static force is calculated from the combined vehicle and vehicle restraint deflection calculated from the equation in Section 2.4. The specified 100 mm vehicle deflection must be assumed when calculating the target force.

The tests should be at agreed locations, chosen as visually the most onerous, and aim to verify: -

- the quality of the vehicle restraint materials (especially after visible deterioration), and
- the strength of the immediate supporting structural members (the deck or columns), and
- the strength of the fixings and their attachment to the members of the car park structure.

The pseudo-static tests should be made at a selection of the dynamic test positions to achieve the verifications necessary. As the force is progressively applied to the edge restraint, the consequent deflections should be used in the equation in Section 2.4 to calculate a revised, lower target force. This iterative process should be continued until the applied force exceeds the target force.

5. PROPOSED ACCEPTANCE CRITERIA.

5.1 Limitations on Acceptance Criteria

The principles for acceptance described in Sections 5.2 for the System Compliance Test, and 5.3 for the Installation Compliance Test have been derived from this test programme.

There is no necessity to dynamically test vehicle restraint systems for the increased force opposite a long access, (or for the reduced force on a ramp,) provided the following installation practices are adopted.

Horizontally-spanning vehicle restraints will normally be suitable to withstand the enhanced (reduced) design force if the beam section's second moment of area is doubled (halved), or if the span is changed to 0.6 (1.6) times its standard value.

Cantilevered vehicle restraint beams need not be modified provided their supporting posts' standard spacing does not exceed 1.6 m. The posts will normally have the second moment of area doubled (halved), or be installed at half (double) the standard spacing.

Monolithic vehicle restraints must have both their thickness and tension steel area changed to 1.4 (0.7) times the standard values, or equivalent moment of resistance provided.

However, in the event that a test is deemed necessary, the long access edge protection test would require an impact velocity of 22.6 km/h, and the ramp edge protection test would require an impact velocity of 11.3 km/h.

5.2. Compliance Test Criteria for a System.

The following principles for acceptance have been derived from this test programme, and should be met by the System Compliance Tests: -

- The vehicle restraint should arrest the specified impacting masses, without itself failing catastrophically, and without permitting them to ride over the top of the vehicle restraint.
- The vehicle restraint should not deflect by more than the clear distance expected between the original vehicle restraint position and any cladding made with a brittle material. No brittle element should be damaged by the impact.
- The total deflection of any vehicle restraint should not exceed 600 mm, except at split levels.
- Barriers providing pedestrian restraint should not deflect beyond the edge of the deck, except at split levels.
- Any fixing bolts on which the vehicle restraint support relies for attachment to the structure should neither fail nor pull out. Locating bolts may be beneficially designed to fail in order to restrict damage to the primary structural members (e.g. columns) provided the vehicle restraint beam continues to be restrained in a fail-safe configuration (such as between column flanges).
- Deformation of the vehicle restraint beyond repair is acceptable, since it could be replaced if damaged.

5.3. Compliance Test Criteria for an Installation.

It is expected that at least one Installation Compliance Test will be carried out on each car park when Structural Appraisals take place, at least every 16 years, as recommended by The Inspection and Maintenance of Multi-Storey Car Parks - Interim Guidance[18]. An Installation Compliance Test may also be required if there is concern that components of the system supplied are to a different material specification from those used in the System Compliance Tests.

The following acceptance principles should be met by Installation Compliance Tests: -

- The vehicle restraint should resist the specified applied force, without itself failing catastrophically.
- The vehicle restraint should not deflect by more than the clear distance between its original position and any cladding made with a brittle material. Ductile cladding must be suitably restrained along the top edge to prevent it becoming detached.
- The total deflection of any vehicle restraint should not exceed 600 mm.
- Barriers providing pedestrian restraint should not deflect beyond the edge of the deck, except at split levels.
- Any fixing bolts that the vehicle restraint relies on for support should neither fail nor pull out. Bolts designed to locate the vehicle restraint beam may fail provided the beam derives further support in a fail-safe configuration.
- Deformation of the vehicle restraint beyond repair is acceptable provided it cannot lead to progressive collapse. However, it must be replaced if damaged.

6. RESULTS OF DYNAMIC TESTS UNDERTAKEN IN THIS PROJECT.

6.1. Dynamic Test and Pseudo-Static Test Characteristics Compared.

The combination of slippage at connections, and localised yielding at many locations over a wide range of loads, results in many pseudo-static load versus deflection test responses being close to linear. A range of test results is shown in Figure 2.

In the dynamic test situation, the inertia of the vehicle restraint causes a much more rapid rise in load on impact, at a rate approaching that of a rigid vehicle restraint. The precise form of the load increase is a complex function of the vehicle restraint system, and is difficult to predict, but examples are shown diagrammatically on Figure 3. The transient load may exceed the final load. It is the satisfactory response of the entire vehicle restraint system to the transient load that is demonstrated by the proposed dynamic test.

There are two conclusions from these responses. Firstly, the rigid vehicle restraints develop force at greatest rate. Secondly, the more flexible the vehicle restraint is, the greater is the rate of force development than expected.

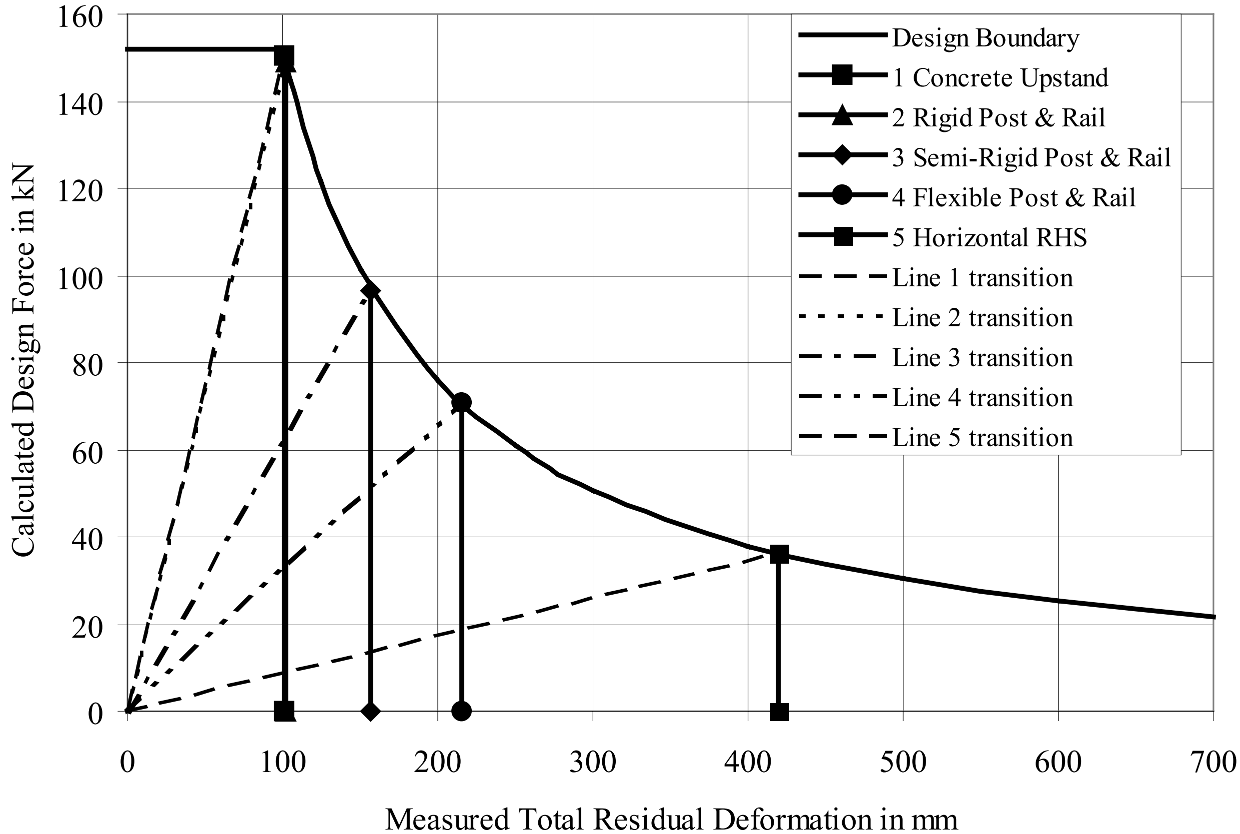

Figure 2. Linear Response Design Expectations.

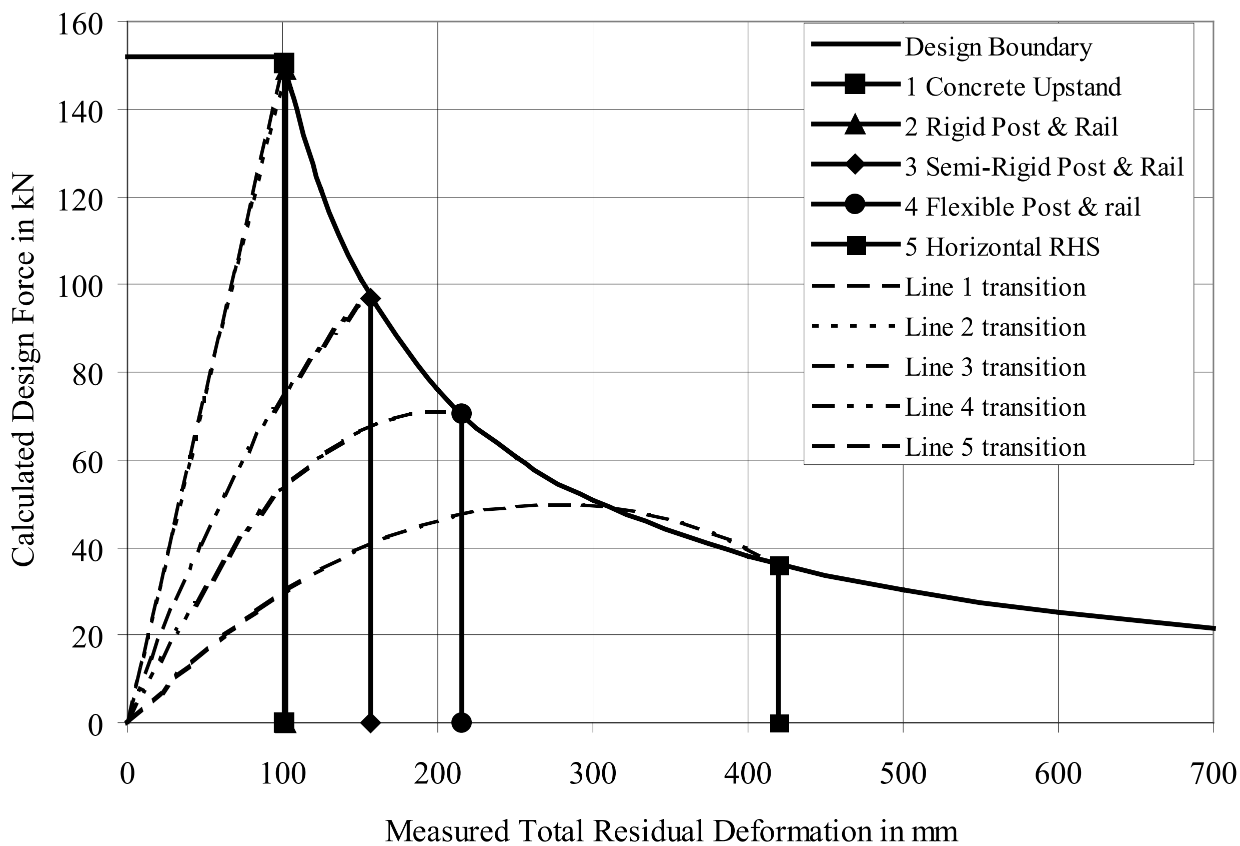

Figure 3. Diagrammatic Actual Response To Impact

6.2. Compliance Test Results for Common Systems Currently in Use.

Tables 2a-f present a summary of the results of the dynamic impact tests carried out to the revised specification outlined above for most edge protection systems in current use. All the tables are for dynamic impacts at 445 mm height. For tables of results for existing installations at 375 mm height, the reader is referred to Edge Protection In Multi-Storey Car Parks - Assessment of Installed Vehicle Restraints[19].

The tables provide results for the following installation systems: -

Table 2a	Cold rolled steel sections spanning horizontally between columns
Table 2b	Hot rolled steel sections spanning horizontally between columns
Table 2c	Motorway safety fence rails mounted on cantilevered posts (impact centred on penultimate post)
Table 2d	Motorway safety fence rails mounted on cantilevered posts (impact centred on an internal midspan)
Table 2e	Motorway safety fence rails mounted on cantilevered posts (impact at nearest possible position to end post)
Table 2f	Monolithic Concrete Upstand walls

Only results that satisfy the proposed acceptance criteria have been included in these tables. Edge protection systems may be deemed equivalent to one of the systems listed in Table 2 (and thus satisfactory), provided they are designed with materials of equivalent specification to at least equal all of the following characteristics:

- mass above deck level (inertia),
- section moment capacity, and
- fixity to the structure.

Test Number	Edge Protection System			Impact Position	Results		Notes
	Vehicle restraint Type	**Supports**	**Frame Fixture**		**Maximum residual deflection at 445 mm height**	**Maximum dynamic deflection (mm)**	
A1	1.5 sine wave 310x85x3 cold-formed section	203x203x52 UC columns @ 2.4 m centres	Direct with 2 sliding P-clips*	Middle of span 2 of 3	358	461	
A2	1.5 sine wave 310x85x3 cold-formed section	203x203x52 UC columns @ 2.4 m centres	Direct with 2 sliding P-clips* & braced ends	Middle of span 2 of 3	243	289	
A3	1.5 sine wave 310x85x3 cold-formed section	203x203x52 UC columns @ 2.7 m centres	Direct with 2 bolted P-clips*	Middle of span 1 of 2	408	507	
A4	2 x 1.5 sine wave 310x85x3 cold-formed section	203x203x52 UC columns @ 2.4 m centres	Direct with 2 sliding P-clips*	Middle of span 2 of 3	99	106	
A5	2 x 1.5 sine wave 310x85x3 cold-formed section	203x203x52 UC columns @ 2.7 m centres	Direct with 2 bolted P-clips*	Middle of span 1 of 2	164	182	
A6	Sigma 300x90x4 cold-formed section	203x203x52 UC columns @ 2.4 m centres	Direct with 2 sliding P-clips*	Middle of span 1 of 2	198	225	
A7	Sigma 300x90x4 cold-formed section	203x203x52 UC columns @ 2.7 m centres	Direct with 2 sliding P-clips*	Middle of single span	297	364	
A8	Sigma 300x90x4 cold-formed section	203x203x52 UC columns @ 2.4 m centres	Directly bolted with one M20 x 8.8 bolt	Middle of single span	174	197	

* 60 mm x 6 mm section fixed by one M20 x 8.8 bolt

Table 2a. Test Programme Results For 445 mm High Impact On Cold Rolled Sections Spanning Horizontally

Test Number	Edge Protection System			Impact Position	Results		Notes
	Vehicle restraint Type	Supports	Frame Fixture		Maximum residual deflection at 445 mm height	Maximum dynamic deflection (mm)	
A9	CHS 193.7x8	356x 368x129 UC Columns @7.5 m centres	Directly bolted to column stiffeners by one M20 x 8.8 bolt	Middle of single span	190	253	
A10	SHS 150x150x8	356x 368x129 UC Columns @7.5 m centres	Directly bolted to column stiffeners by one M20 x 8.8 bolt	Middle of single span	183	265	
A11	CHS 168.3x8	356x 368x129 UC Columns @7.5 m centres	Directly bolted to column stiffeners by one M20 x 8.8 bolt	Middle of single span	320	415	
A12	CHS 168.3x8	356x 368x129 UC Columns @7.5 m centres	Directly bolted to column stiffeners by one M20 x 8.8 bolt	End of single span	116	158	
A13	CHS 193.7x10	356x 368x129 UC Columns @10.0 m centres	Directly bolted to column stiffeners by one M20 x 8.8 bolt	Middle of single span	176	294	
A14	SHS 150x150x10	356x 368x129 UC Columns @10.0 m centres	Directly bolted to column stiffeners by one M20 x 8.8 bolt	Middle of single span	227	399	
A15	CHS 168.3x10	356x 368x129 UC Columns @10.0 m centres	Directly bolted to column stiffeners by one M20 x 8.8 bolt	Middle of single span	328	526	

Table 2b. Test Programme Results For 445 mm High Impact On Hot Rolled Sections Spanning Horizontally

Test Number	Edge Protection System			Impact Position	Results		Notes
	Vehicle restraint Type	**Supports**	**Frame Fixture**		**Maximum residual deflection at 445 mm height**	**Maximum dynamic deflection (mm)**	
A16	1.5 sine wave 310x85x3 cold-formed section centre level 445 mm	Cantilevered post* in socket 3 @ 1.6 m centres	Through bolt to solid slab 110 mm thick	Centred on support 2 of 3	49	136	Cantilever type B
A17	1.5 sine wave 310x85x3 cold-formed section top level 560 mm	Cantilevered I+ on baseplate. 3 @ 1.6 m centres	Through bolt to solid slab 110 mm thick	Centred on support 2 of 3	1.5	15	Cantilever type A
A18	1.5 sine wave 310x85x3 cold-formed section top level 560 mm	Cranked-L# post 3 @ 1.6 m centres	Through bolt to solid slab 110 mm thick	Centred on support 2 of 3	123	445	Cantilever type C

* 130 x 75 UB in 100 x 190 x tapering 200 to 100 high socket on 330 x 280 x 8 base with four M12 x 8.8 bolts at 230 lever arm

+ 130 x 75 UB welded to 330 x 280 x 10 base with 100 x 8 stiffening brace, with four M20 x 8.8 bolts at 270 lever arm

100 x 14 section with 320 base length, 205 standoff at 250 height, with one M20 x 8.8 bolt at 230 lever arm

Table 2c. Test Programme Results For 445 mm High Impact Against Rails Mounted On Cantilevered Posts (penultimate posts)

Test Number	Edge Protection System			Impact Position	Results		Notes
	Vehicle restraint Type	Supports	Frame Fixture		Maximum residual deflection at 445 mm height	Maximum dynamic deflection (mm)	
A19	1.5 sine wave 310x85x3 cold-formed section centre level 445 mm	Cantilevered post* in socket 5 @ 1.6 m centres	Through bolt to solid slab 110 mm thick	Middle of span 2 of 4	37	84	Cantilever type B
A20	1.5 sine wave 310x85x3 cold-formed section top level 560 mm	Cantilevered I+ on baseplate. 5 @ 1.6 m centres	Through bolt to solid slab 110 mm thick	Middle of span 2 of 4	1.0	9.0	Cantilever type A
A21	Open trapezoidal box C 150-200x150x4 cold-formed section top level 560 mm	Cantilevered I+ on baseplate. 5 @ 1.6 m centres	Through bolt to solid slab 110 mm thick	Middle of span 2 of 4	0.5	7.0	Cantilever type A
A22	1.5 sine wave 310x85x3 cold-formed section top level 560 mm	Cranked-L# post 5 @ 1.5 m centres	Through bolt to solid slab 110 mm thick	Middle of span 2 of 4	83	262	Cantilever type C

* 130 x 75 UB in 100 x 190 x tapering 200 to 100 high socket on 330 x 280 x 8 base with four M12 x 8.8 bolts at 230 lever arm

\+ 130 x 75 UB welded to 330 x 280 x 10 base with 100 x 8 stiffening brace, with four M20 x 8.8 bolts at 270 lever arm

\# 100 x 14 section with 320 base length, 205 standoff at 250 height, with one M20 x 8.8 bolt at 230 lever arm

Table 2d. Test Programme Results For 445 mm High Impact Against Rails Mounted On Cantilevered Posts (internal spans)

Test Number	Edge Protection System			Impact Position	Results		Notes
	Vehicle restraint Type	**Supports**	**Frame Fixture**		**Maximum residual deflection at 445 mm height**	**Maximum dynamic deflection (mm)**	
A23	1.5 sine wave 310x85x3 cold-formed section centre level 445 mm	Cantilevered post* in socket 5 @ 1.6 m centres	Through bolt to solid slab 110 mm thick	End of span 1 of 4	31	168	Cantilever type B
A24	1.5 sine wave 310x85x3 cold-formed section top level 560 mm	Cantilevered I+ on baseplate. 5 @ 1.6 m centres	Through bolt to solid slab 110 mm thick	End of span 1 of 4	1.5	13	Cantilever type A
A25	Open trapezoidal box C 150-200x150x4 cold-formed section top level 560 mm	Cantilevered I+ on baseplate. 5 @ 1.6 m centres	Through bolt to solid slab 110 mm thick	End of span 1 of 4	4.0	11	Cantilever type A
A26	1.5 sine wave 310x85x3 cold-formed section top level 560 mm	Cranked-L# post 5 @ 1.5 m centres	Through bolt to solid slab 110 mm thick	End of span 1 of 4	103	313	Cantilever type C

* 130 x 75 UB in 100 x 190 x tapering 200 to 100 high socket on 330 x 280 x 8 base with four M12 x 8.8 bolts at 230 lever arm

+ 130 x 75 UB welded to 330 x 280 x 10 base with 100 x 8 stiffening brace, with four M20 x 8.8 bolts at 270 lever arm

100 x 14 section with 320 base length, 205 standoff at 250 height, with one M20 x 8.8 bolt at 230 lever arm

Table 2e. Test Programme Results For 445 mm High Impact Against Rails Mounted On Cantilevered Posts (end posts)

Test Number	Edge Protection System			Impact Position			Notes
	Vehicle restraint Type	Supports	Frame Fixture		Maximum residual deflection at 445 mm height	Maximum dynamic deflection (mm)	
A27	175 mm thick concrete with 600 mm upstand	Cantilever with T12 @180 mm reinforcement	Monolithic	Centre of 7.36 m long wall	1.0	2.0	Rebars cast into 75 mm C35 topping on 150 mm hollowcore slabs
A28	175 mm thick concrete with 600 mm upstand	Cantilever with T12 @180 mm reinforcement	Monolithic	End of 6.12 m long wall	5.5	11	Rebars cast into 75 mm C35 topping on 150 mm hollowcore slabs

Table 2f. Test Programme Results For 445 mm High Impact Monolithic Concrete Upstand Walls

6.3. Vehicle Restraint Deflections and Bolt Forces

Table 3 gives tensile bolt forces measured during the test programme. The forces were obtained when the dynamic impact load was applied at 445 mm height, symmetrically about the centreline of the middle post of a three-post installation. The vehicle restraint posts were through-bolted to the deck. Both measured total loads on the post and maximum loads per bolt are quoted.

Vehicle restraint Rail Type	Post Support Type	Deflection at 445 mm height (mm)	Total Number of Bolts per Post	Maximum Total Load* per Post (kN)	Maximum Load per Bolt (kN)
Standard motorway	Cantilever A	2	4 (2 tensile)	189.9	130.0
Standard motorway	Cantilever B	57	4 (2 tensile)	123.2	80.0
Standard motorway	Cantilever C	115	1	58.7	58.7

Table 3. Measured vehicle restraint deflections & bolt loads after 445 mm high impact {* Total Load equals Sum of loads on tensile bolts(s).}

7. EDGE PROTECTION DESIGN.

7.1 General

Tables 2a to 2e contain the deflection data necessary to check whether a particular system is satisfactory in the design of a new installation. For systems cantilevered from the deck, the maximum deflection quoted is in most cases the top deflection of the supporting post. However, in systems which utilise thin sprung steel sections, and for all horizontally spanning systems, the rail deflection is most critical. The maximum residual deflection is quoted at the impact height in all cases to facilitate ease of comparison.

Any proposed installation using an edge protection system identical to one of those for which test results are presented in the table may therefore be used without the need for further dynamic testing, provided components of the system comply with the published specification.

The maximum dynamic deflection quoted in the tables provides a lower limit to the clear distance between the proposed edge protection and brittle cladding. It also defines the position to which ductile cladding must be able to deflect without becoming detached from the structure.

The maximum residual deflection quoted in the table gives an indication of the likely deflection that will be obtained in an Installation Compliance Test. These values alone should not be used to determine the force required in the Installation Compliance Test. The force and deflection interaction should be checked during the test as described in Section 4.2.

Proposals for a design procedure for vehicle restraint systems were developed as part of the Project. They are given below: -

- to identify the appropriate system to be installed
- to use the maximum dynamic deflection value from the Table 2 to determine the permitted proximity of cladding, or if the chosen system does not appear in Table 2 conduct a System Compliance Test
- refer to the Manufacturer's literature for installation details,
- conduct an Installation Compliance Test only if there are doubts concerning the vehicle restraint quality or concerning the fixings.

7.2. Partial Factors

The load partial factors are those used in the structural design of any building, treating the vehicle impact as an accidental load case and the pedestrian balustrade loading as a repeatable live load.

7.2.1. Load Partial Factors

For design purposes, the vehicle impact load is factored by 1.05 and the lateral balustrade load is factored by 1.6.

The material partial factor for a bolt fastening may be taken as the ratio of the bolts' proof stress to the specified design stress in BS5950. For grade 8.8 bolts in pure tension this is 1.74.

There is no single partial factor for all types of anchor bolt fixed into concrete. Suppliers are encouraged to quote in their literature both the type of bolt and the partial factor used for the relevant load conditions. Further reductions must be made if the failure cone geometry overlaps the slab edge or other bolt failure cones.

When testing systems or installations, the vehicle impact load partial factor is 1.0, and the lateral balustrade load factor is 1.25

7.2.2. Material Partial Factors

For design purposes, a material partial factor of 1.0 is used for the characteristic (5 percentile) material strength of both cold-formed and hot-rolled steelwork.

Spring steel is not normally used in structural buildings, so no appropriate partial factor is stated in the Standards for this less ductile material. It is recommended that manufacturers using such materials should define clearly in their literature the steel grade and material partial factor used.

Design of reinforced concrete sections using BS8110 includes material partial factors of 1.5 for concrete bending and axial strengths, 1.3 for deflection, 1.25 for concrete shear strength, and 1.05 for steel reinforcing bars.

Interim guidance on the design of reinforced concrete structures using fibre composite reinforcement, given by the Institution of Structural Engineers, recommends the generic material partial factors given in Table 4.

	Strength–related design conditions	Stiffness-related design conditions
E-glass fibres	3.6	1.8
Aramid fibres	2.2	1.1
Carbon fibres	1.8	1.1
Bond strength	1.4	

Table 4. Partial Factors for Composite Reinforcing Materials.

7.3. Vehicle Restraint Fixing Design.

7.3.1. Design Of Anchor Bolts To Fix Cantilevered Vehicle Restraints To Decks.

Two common design requirements for bolts fixing vehicle restraints to the deck are to:

- Identify suitable fixings for a new connection, knowing the characteristics of the vehicle restraint to be installed, and
- Ascertain whether a given fixing is adequate.

Fixing bolt manufacturers generally specify the bolt capacity in unreinforced concrete. More specific manufacturer's information of strengths in reinforced slabs may be required to obtain an acceptable design solution to the first of these requirements. Alternatively, the pseudo-static Installation Compliance Test will demonstrate the suitability of a fixing arrangement into a particular structure.

When vehicle restraints require replacement, or a manufacturer identifies a fixing to use, there is often a need to demonstrate using an on-site test that the bolt will provide an adequate tensile strength. The most common test used is a direct tensile test of the fixing in the existing concrete installation. It is convenient to decide what anchor bolt test strength is acceptable for the given installation, without needing to test the entire installation.

Results given in Table 3 (Section 6.3), obtained from this test programme, permit both design cases to be addressed. Subsequent sections describe the proposed methodology.

7.3.2. Fixing Bolts

Bolted connections at metal-to-metal contact points should be designed in accordance with BS5950 or other appropriate standard.

Fixings for cantilevered vehicle restraints that are fixed directly to the concrete deck have been found to be particularly vulnerable to corrosion when exposed to poor drainage conditions. Good drainage of car park decks is of paramount importance. There are advantages in mounting cantilevered post supports for vehicle restraint systems on plinths to prevent puddles remaining around the fixings. Use of fixings that are removeable for inspection is an advantage.

Holes for fixings should be positioned to avoid reinforcement. Diamond drilling causes less soffit breakout on through-slab holes. Sealing the bolt into its hole will help to prevent water ingress and corrosion.

Vehicle restraints should have fixings that are rigidly anchored to the concrete. Through-bolts with plate washers beneath, of a size to resist the predicted combination of tension and shear forces are satisfactory. Setting the posts on plinths will enhance durability. Use of stainless components is also advantageous, with their strength typically 87.5% of the same size fixing of grade 8.8 steel.

Other types of proprietary fixing may be suitable, but their ability to remain anchored into the slab when subject to successive load applications should be demonstrated. Suitability can be confirmed by pull-out tests that repeat the predicted combination of loads four times prior to application of a failure load to determine the overall safety factor. This is to prevent minor impacts reducing the fixing capacity without that reduction being apparent prior to a significant impact. The load capacity that the fixing should be tested for is the maximum load per bolt from Table 3 corresponding to the system in use, modified by partial safety factors and also, where necessary, the adjoining bolt proximity and edge proximity factors from Sections 7.3.3.

Some basic information necessary to complete the calculations is reproduced in Section 7.3.4. for convenience.

7.3.3. Bolt Proximity Reduction Factors

Where more detailed design information for particular fixings is not available, the following reduction factors may be used where bolts are in close proximity with each other, or with the edge of the deck.

The edge proximity reduction in strength factor, k_e, may be taken[20] as

$$k_e = 0.20\ (l_e / l_{min}) + 0.5 \qquad \leq 1.0$$

where l_e is the bolt centre to slab edge distance,
l_{min} is the manufacturer's specified minimum fixing embedment length, and
$l_{min} < l_e < 2.5\ l_{min}$

Also, the adjoining bolt proximity reduction in strength factor, k_o, may be taken[20] as

$$k_o = 0.15\ (l_o / l_{min}) + 0.5 \qquad \leq 1.0$$

where l_o is the bolt centre spacing,
l_{min} is the manufacturer's specified minimum fixing embedment length, and
$l_{min} < l_e < 3.0\ l_{min}$

7.3.4. Other Fixing Design Data

The following data is reproduced from other British Standards for convenience. These specific extracts are needed to complete the fixing design procedure.

BS5950 specifies a design tensile stress in a grade 8.8 bolt as 450 N/mm^2 in direct tension, reducing to 375 N/mm^2 in pure shear.

BS8110 specifies a concrete friction coefficient against a steel surface of 0.4

Bolt Size	**Area (mm)**
M10	58.0
M12	84.3
M16	157
M20	245
M24	353

Table 5. Bolt Tensile Stress Areas (from BS4190)

7.4 Forces Applied to the Structural Frame.

The forces to which the structural frame may be subjected from the vehicle restraint system can be derived from the foregoing data in two ways.

When vehicle impact is directly against a column or other member of the structural frame, the member should be designed to withstand a force of 150 kN applied at the point of impact (normally 445 mm above the deck surface).

When impact is indirectly applied, via a vehicle restraint rail and / or post, then the forces on the structure can be determined as the reactions to the bolt design forces evaluated in Section 7.3.

8. CONCLUSIONS FROM THE RESEARCH PROGRAMME.

The following conclusions have arisen from this Project:

1. A proposed design specification for edge protection performance has been developed (see Section 3). This proposed specification is summarised as follows, with differences from the requirements in the current Standards underlined:
    - **There is no proposed change of the 2500 kg design vehicle for vertical loading, or the corresponding 1500 kg mass for horizontal impact loading.**
    - **No change to the 16 km/h impact velocity is proposed.**
    - **No change is proposed to the 1.5 m impact width.**
    - **<u>Adoption of an impact height of 445 mm, raised from 375 mm, is proposed.</u>**
    - **<u>It is proposed that a horizontal impact at 445 mm height be used to define the design impact.</u>**
    - **The present assumption of 100 mm vehicle deformation appears to be realistic for pseudo-static loading. No change is proposed to this value.**
    - **<u>Adoption of a full-scale dynamic compliance test is proposed for each edge protection system to prove it is able to resist the high dynamic flow stresses.</u>**
    - **A pseudo-static test is retained for use on installations within car parks.**
    - **<u>Deflection limitations are proposed for both test methods.</u>**
    - **The ramp edge protection requirement accords with the highway safety fence requirement, and is adequate.**
    - **<u>The same requirements should apply to stair well edge protection as at the edge of the deck.</u>**
    - **<u>In the absence of traffic calming measures, all edge protection with greater than 20 m approach length should be designed for twice the static design force applied at 445 mm height.</u>**
    - **<u>There is scope for relaxation of deflection criteria at split level deck boundaries.</u>**
    - **Pedestrian edge restraints should be provided to a height of 1.1 m <u>measured above the highest foothold reached by a rise of less than 550 mm</u>.**
    - **Provided pedestrians are directed not to use the vehicle ramps, the pedestrian guard may be omitted on ramps.**

2. Two full-scale load tests, one dynamic and the other pseudo-static, have been developed to determine the compliance of a vehicle restraint system with the requirements of the proposed design specification (see section 4).

3. On the basis of the dynamic test programme and practical requirements relating to system performance, principles for acceptance of restraint systems are proposed (see Section 6).

4. A range of proprietary vehicle restraint systems have been tested using the proposed dynamic test procedure and have been found to comply with the proposed acceptance criteria (see section 6). Results for tests on similar edge protection systems using the current standard impact height of 375 mm are presented in reference [19].

A number of new or different vehicle restraint combinations were included in the original research proposal, for example, a wire system and a combined vehicle restraint cum pedestrian guard system. The new vehicle restraint systems have not been developed in time to be included in this Project, and some other proposed constructions differed little from tests that were completed. Some tests were developmental by nature and have been excluded since they did not produce useful valid results.

5. Proposals for edge protection design to meet the requirements of the design specification have been developed (see Section 7). Sufficient data is presented for the design of a range of types of new edge protection installation.

6. The foregoing proposals have support from the car park vehicle restraint supply industry, and have been publicised at seminars and conferences organised by

- The Institution of Civil Engineers
- The Institution of Structural Engineers
- The British Parking Association
- The British Cement Association
- TRL Limited

The findings are already programmed for presentation at two further conferences.

Additionally, the conclusions from this Project are being introduced to the forthcoming revisions to the ICE Car Park Inspection Guide and the IstructE Design Guide for Car Parks.

Papers for publication in the technical press are being written also.

9. ACKNOWLEDGEMENTS.

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