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Base Isolation and Damage-Resistant Technologies for Improved Seismic Performance of Buildings

A report written for the Royal Commission of Inquiry into Building Failure Caused by the Canterbury Earthquakes

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1 SUMMARY

Modern methods of seismic design (since the 1970s) allow structural engineers to design new buildings with the aim of predictable and ductile behaviour in severe earthquakes, in order to prevent collapse and loss of life. However some controlled damage is expected, which may result in the building being damaged beyond economic repair after severe shaking.

Seismic protection of structures has seen significant advances in recent decades, due to the development of new technologies and advanced materials. It has only been recently recognised world-wide that it is possible to design economical structures which can resist severe earthquakes with limited or negligible structural damage.

There are two alternative ways of designing buildings to avoid permanent damage in severe earthquakes; base isolation and damage-resistant design. Base isolation requires the building to be separated from the ground by isolation devices which can dissipate energy. This is proven technology which may add a little to the initial cost of the building, but will prove to be less expensive in the long term.

Damage-resistant design is developing rapidly, in several different forms. These include rocking walls or rocking frames, with or without post-tensioning, and a variety of energy dissipating devices attached to the building in different ways. If not already the case, damage-resistant design will soon become no more expensive than conventional design for new buildings.

1.1 Scope

- This report is generally about structural damage to multi-storey buildings.
- Single family houses and other small residential buildings are beyond the scope of the report.
- Design to prevent damage to non-structural elements of buildings is also very important, but is not covered in this report.
- The emphasis is on design and construction of new buildings, not repair or reinstatement of damaged buildings, nor strengthening of existing buildings, although damage-resistant design can also be used for these purposes.
- This report does not address foundation engineering or geotechnical issues.

2 BACKGROUND

Many people are asking *"Why were so many modern buildings damaged beyond economic repair in the Christchurch earthquakes?"*The simple answer is that the current design methods rely on some damage to protect the buildings, and in addition, the ground shaking in Christchurch on 22 February was significantly more severe than the level of shaking used to design modern buildings. This report will focus on the causes of, and responses to, this damage caused by shaking. The other main reason for damage is the unprecedented soil liquefaction, lateral spreading, and foundation failure, which can only be managed in the future by careful site investigation and high quality geotechnical advice for the design of all buildings and foundations.

Considering the severity of the earthquake, the damage to buildings caused by ground shaking in Christchurch was somewhat less than expected by many structural engineers. Most of the old unreinforced masonry buildings were severely damaged, unless they had been systematically strengthened. Moderately aged reinforced concrete and reinforced masonry buildings generally suffered significant structural damage but no collapse, with two disastrous exceptions. Many well designed houses and industrial buildings did not have major problems which cannot be repaired.

The biggest concern of structural engineers is with those modern multi-storey buildings which have been damaged beyond economic repair. The seeds of this costly damage lie in the seismic design philosophy embedded in international building codes, based on the principle that a minor earthquake should cause no damage, a moderate earthquake may cause repairable damage, and a large earthquake, such as considered by modern design codes, can cause extensive damage but no collapse or loss of life.

As a very brief summary of the design process, when a structural engineer is designing a building for earthquake resistance, it is necessary to provide the building structure with the three key attributes of strength, stiffness, and ductility:

- Strength is necessary so that the building can resist lateral forces without failure of the whole structure, or failure of any critical parts. Increasing the strength of a structure costs money, but the required strength can be reduced if sufficient ductility is provided, as described below.
- Stiffness is essential to limit the lateral deflections of the building during the earthquake, to ensure that secondary structural elements such as stairs, facades and partitions are not damaged. The stiffness (or flexibility) of a building is a measure of how much lateral movement will occur when it is subjected to lateral loads. Modern building codes specify a maximum lateral deflection between two floors of about 75mm (2.5% of 3 metres) under the design level earthquake loading.
- Ductility is essential to avoid sudden failure after a building's strength limit is exceeded. Ductile materials like steel are often used locally in a building to increase the ductility of the whole building. Ductile buildings are subjected to much lower earthquake forces, making seismic design affordable, but they can be left with permanent structural damage. Ductility requires a building to undergo large displacements without losing overall strength in any of its critical elements.

A dilemma facing structural engineers is the trade-off between strength and ductility. Modern building codes provide for the design of safe but affordable buildings, by encouraging "capacity design" which allows for controlled damage in carefully selected ductile parts of the structure without exceeding the capacity of other components. In a severe earthquake, ductile buildings designed to minimum standards may have considerable damage in the ductile regions. Many Christchurch buildings have such damage, as expected, and some will need to be demolished because repair is not economically viable.

This dilemma raises another question *"Can structural engineers economically design new buildings for no structural damage?"* There are two recognised strategies for limiting damage in a major earthquake, to provide both life safety and property protection. These two are increased strength and stiffness, and energy dissipation to reduce damage:

1. The simplest and oldest method of limiting damage in a major earthquake is to overdesign the structure so that no damage occurs. This can be achieved by increasing the design level of strength and stiffness well above that required to resist the maximum expected earthquake. In this case the building will remain elastic in the design level earthquake, but ductility is still required to prevent collapse in a more severe earthquake. Overdesign may be an economical solution for houses and low-rise buildings such as factories and schools, but for multi-storey buildings this solution is very expensive, and usually unaffordable.
2. Base isolation will reduce damage in a major earthquake, by reducing the response of the building by partially isolating it from the shaking ground. This is done by placing the building on base-isolation units such as the lead-rubber bearings under Christchurch Women's Hospital, also used at Te Papa, and Parliament Buildings in Wellington. These devices allow an economical building to be built on an expensive foundation, with the total cost being only a little more than conventional design.

   Damage-resistant structures can also be designed to absorb energy in other parts of the structure, so that the building rocks back and forth in a major earthquake, returning to an undamaged position after the shaking. This combines ductility to reduce the design forces with little or no residual damage. New Zealand engineers are contributing to international developments in this field, including the recently completed reinforced concrete Endoscopy building at Southern Cross Hospital in Christchurch, TePuni Village steel building at Victoria University in Wellington, and the new NMIT timber building in Nelson. Experimental research at the University of Canterbury has supported these developments, which will allow new damage-resistant buildings at no more cost than conventional building designs.

The recent Christchurch earthquakes present a huge challenge and a huge opportunity to professional engineers. Now is the time to show how Kiwi structural engineers and geotechnical engineers can contribute to a sustainable cityscape for the new Christchurch, designing attractive and safe modern buildings which will not suffer the fate of today's older buildings in future earthquakes. The tools are available, with only a modest investment in building codes, education, and research necessary to make it happen.

3 PERFORMANCE-BASED DESIGN

This chapter describes the current international philosophy for seismic design, explaining why such large levels of structural damage occurred in the Christchurch earthquakes. Future standards for reducing the level of earthquake damage are also discussed.

3.1 Capacity Design

The seismic design philosophy embedded in international building codes is based on the principles that

- a minor earthquake should cause no damage,
- a moderate earthquake may cause repairable damage,
- a huge earthquake can cause extensive damage but no collapse or loss of life.

Recognising the economic disadvantages of designing buildings to withstand earthquakes elastically as well as the associated disastrous consequences following an event with an higher-than-expected earthquake intensity (i.e. as observed in Kobe 1995, and in Christchurch 2011), current seismic design philosophies favour the design of "ductile" structural systems. Ductile structures are able to withstand several cycles of severe loading, with materials stressed in the inelastic range, without losing structural integrity.

This design philosophy, referred to as "capacity design", was developed in the 1960s and 1970s by Professors Bob Park and Tom Paulay at the University of Canterbury. The basic steps in this design philosophy are to ensure that the "weakest link of the chain" within the structural system is located where the designer wants it, and that this weak link will behave as a ductile "fuse", protecting the structure from undesirable brittle failure. This will allow the structure to sway laterally in a severe earthquake without collapsing.

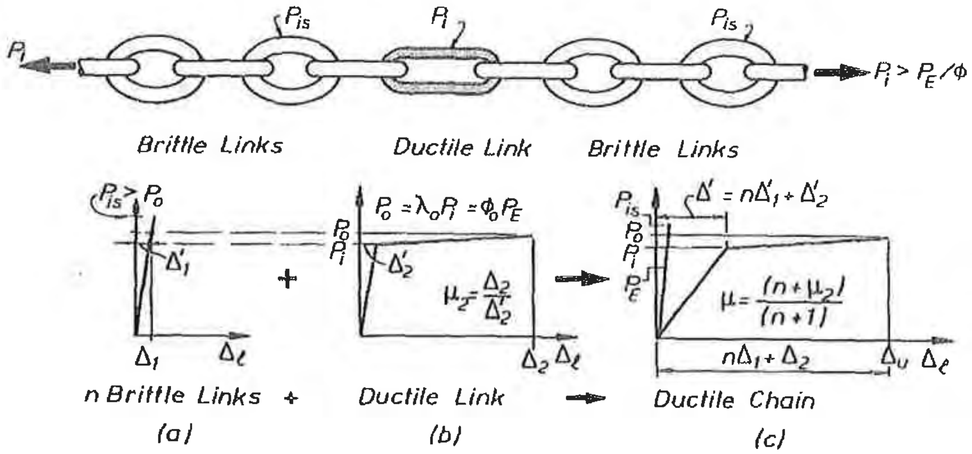


Figure3.1. Capacity design based on the weakest link of a chain (Paulay and Priestley, 1992).

For a moment-resisting frame structures, capacity design will ensure a "strong column – weak beam" mechanism as shown in Figure 3.2(b), which will prevent the possibility of highly undesirable soft-storey mechanisms as shown in Figure 3.2(a), possibly leading to "pancake" collapses. For wall structures, a plastic hinge will occur at the base of the wall as shown in Figure 3.2(c), and in coupling beams between coupled walls as shown in Figure 3.2(d).

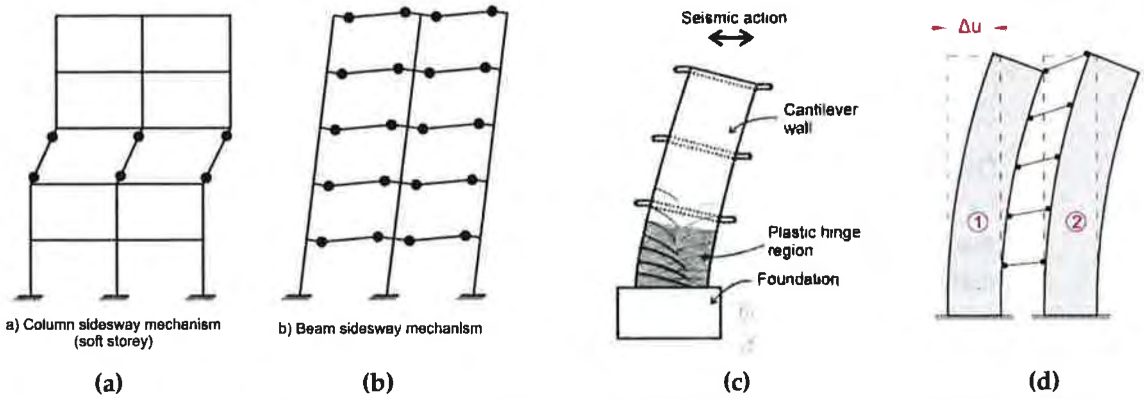


Figure3.2. Plastic hinge locations in multi-storey buildings: (a) Frame with column side-sway mechanism. (b) Frame with beam side-sway mechanism. (c) Plastic hinge at base of multi storey shear wall. (d) Plastic hinges in beams of coupled shear wall.

Reinforced concrete building with masonry infill (Turkey, 1999)

Three-storey apartment building which collapsed to two storeys (Christchurch 2011)

Figure 3.3. Examples of soft-storey collapses in multi-storey buildings.

Regardless of the main structural material (i.e., concrete, steel, or timber), traditional ductile systems rely on the inelastic behaviour of the building. The structural damage is intentionally concentrated within selected discrete "sacrificial" regions of the structure, typical referred to as plastic hinges, most often at beam ends in moment-resisting frames or at the base of cantilevered structural walls. Soft storey collapses are not acceptable.

3.1.1 Ductility

Many of the observed problems in the Christchurch earthquakes result from the large level of *ductility* (inelastic deformation) being activated during the severe earthquakes. Ductile buildings do not have the sudden and catastrophic failures seen in unreinforced masonry buildings and older commercial buildings. The plastic hinge zones accommodate the large displacements during the earthquake, by absorbing energy through controlled damage in selected parts of the building. Design for ductility requires that buildings have the capacity for large displacements without significant loss of strength. Designers are strongly encouraged to provide ductile structures by their engineering education, modern building codes, building regulators, and the owners of the buildings who want to minimise construction costs.

With good design in all other respects, ductility is highly desirable because:

- Ductile components of buildings can absorb energy from earthquake shaking.
- Ductile buildings are required to resist lower seismic forces than buildings designed for elastic response, resulting in less expensive components. (For example, a typical multi storey building designed for a ductility factor of 4.0 will can be designed to resist lateral forces only about one quarter of those for a non-ductile building.)
- Ductile buildings will not suffer sudden collapse when the strength limit or displacement limit is exceeded, compared with more fragile or brittle buildings.
- Ductile buildings have built-in protection for an unpredictable earthquake much larger than the design-level earthquake.

However, if a very severe earthquake demands a high level of ductile deformation, as in the Christchurch earthquakes, ductile buildings can be left with permanent structural damage, which is very expensive to repair.

Ductility will always be a desirable attribute of modern building design, but this must be combined with new design methods which reduce the residual damage, even after the building has been subjected to large deformations. Ductile structures must be carefully designed and detailed to ensure that the required ductility can be provided as intended, especially if the design is for a high level of ductility.

Figure 3.4 (from Paulay and Priestley 1992) shows the strength-displacement relationship for different levels of ductility in a building. It can be seen that the strength required to resist seismic forces decreases as the designer-selected ductility increases from elastic response to fully ductile response. The total displacement of the building is similar for all cases, regardless of the level of ductility selected.

For more information on ductile design, standard references should be consulted, including Paulay and Priestley (1992), Charleson (2008), Dowrick (1988), Priestley et al (2007).

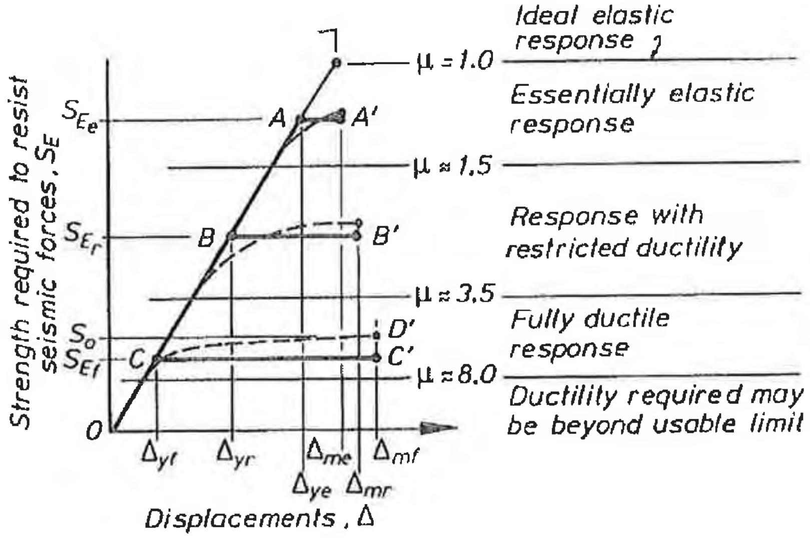


Figure 3.4. Relationship between strength and ductility (Paulay and Priestley 1991).

3.1.2 Code-based "acceptable" level of damage

In the last decade, in response to a recognised urgent need to design, construct and maintain facilities with better damage control following an earthquake, an unprecedented international effort has been dedicated to the preparation of a new philosophy for the design and construction of buildings, from the conceptual design to the detailing and final construction.

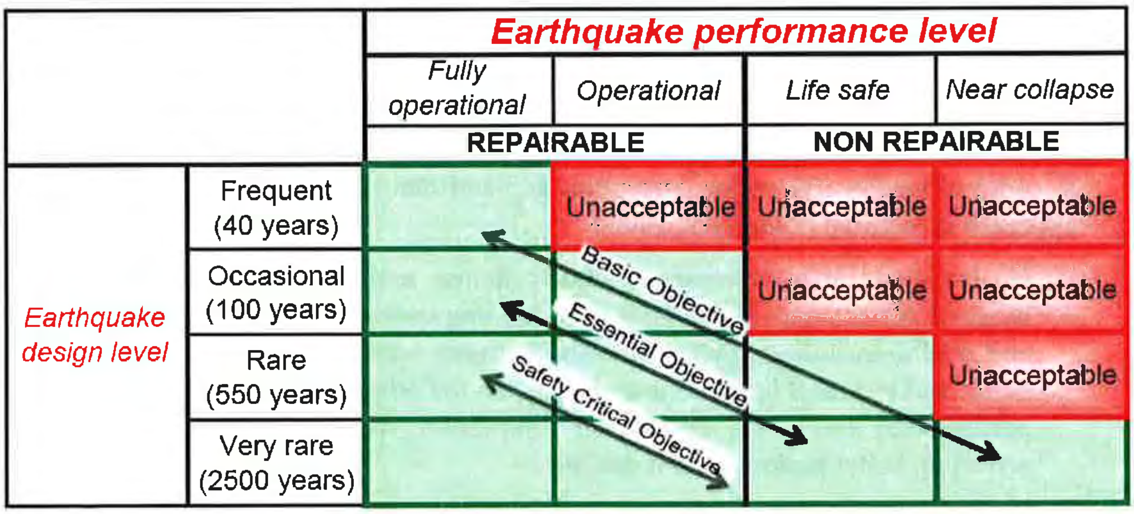
In the comprehensive document prepared by the SEAOC Vision 2000 Committee (1995), Performance Based Seismic Engineering (PBSE) has been given a comprehensive definition, consisting of:

> *"a set of engineering procedures for design and construction of structures to achieve predictable levels of performance in response to specified levels of earthquake, within definable levels of reliability"*

According to a performance-based seismic engineering approach, different levels of structural damage and, consequently, different levels of repair costs must be expected and, depending on the seismic intensity, be typically accepted as an unavoidable result of the inelastic behaviour.

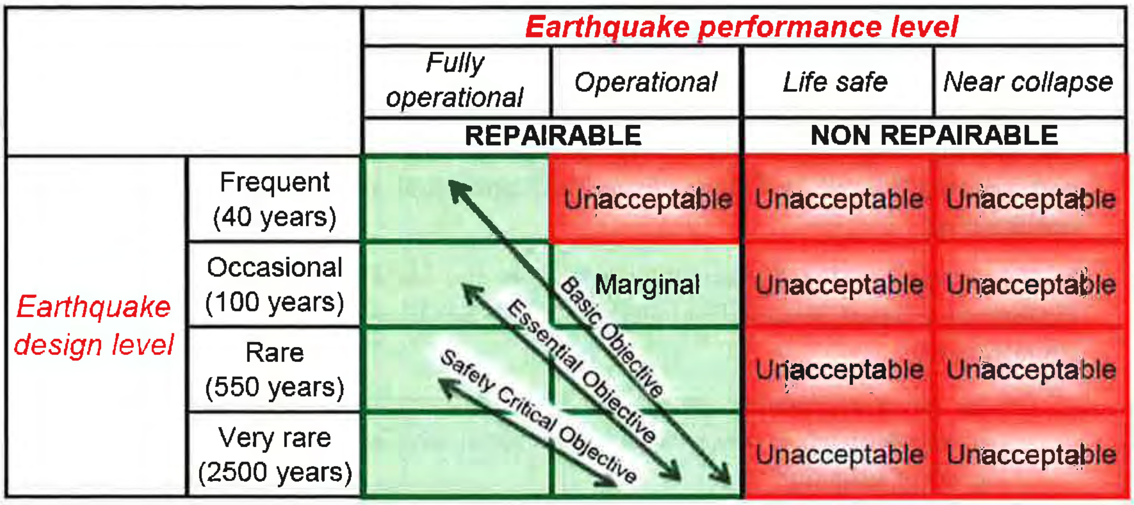
Within this proposed framework, expected or desired performance levels are coupled with levels of seismic hazard by performance design objectives as illustrated by the Performance Objective Matrix shown in Figure 3.5, adapted from SEAOC (1995).

Performance levels are an expression of the maximum acceptable extent of damage under a given level of seismic ground motion, thus representing losses and repair costs due to both structural and non-structural damage. As a further and fundamental step in the development of practical PBSE guidelines, the actual conditions of the building as a whole should be expressed not only through qualitative terms, intended to be meaningful to the general public, using general terminology and concepts describing the status of the facility (i.e., Fully operational, Operational, Life safety and Near collapse as shown in Figure 3.5) but also, more importantly, through appropriate technically-sound engineering terms and parameters, to assess the extent of damage (varying from negligible to minor, moderate and severe) for single structural components or non-structural elements (ceiling, partitions, claddings/facades, content) as well as of the whole system.



		Earthquake performance level			
		Fully operational	*Operational*	*Life safe*	*Near collapse*
		REPAIRABLE		**NON REPAIRABLE**	
Earthquake design level	Frequent (40 years)		Unacceptable	Unacceptable	Unacceptable
	Occasional (100 years)			Unacceptable	Unacceptable
	Rare (550 years)				Unacceptable
	Very rare (2500 years)				

Figure 3.5. Current Performance Objective Matrix (modified from SEAOC, 1995).



		Earthquake performance level			
		Fully operational	Operational	Life safe	Near collapse
		REPAIRABLE		NON REPAIRABLE	
Earthquake design level	Frequent (40 years)		Unacceptable	Unacceptable	Unacceptable
	Occasional (100 years)		Marginal	Unacceptable	Unacceptable
	Rare (550 years)			Unacceptable	Unacceptable
	Very rare (2500 years)			Unacceptable	Unacceptable

Figure 3.6. Proposed modification to Performance Objective Matrix.

3.1.3 Definition of Damage-Resistant Design

Before discussing the damage-resistant techniques, it is first necessary to define terms. It is actually not possible to design and build structures which are damage-resistant under all earthquakes, so the term "damage-resistant" should be used with care. In the context of this document, it simply means that there should be less damage than in existing construction during design level earthquake excitation. A structure which satisfies this criteria should also be available for occupation soon after the very large shaking associated with the Maximum Considered Earthquake (MCE) event.

3.1.4 Reality Check: is this enough?

It is clear from the cost of damage in Christchurch that the general public and their insurers had remarkably different expectations of the likely behaviour of an "earthquake-proof" building, compared with the building designers and the territorial authorities who consented the buildings in the knowledge that some damage was inevitable. All stakeholders clearly expected full life safety and collapse prevention, but the observed level of damage was certainly not expected by the building owners and occupiers and their insurers.

A broad consensus between the public, politicians and the engineering and scientific communities would agree that severe socio-economical losses due to earthquake events, as observed in Christchurch, are unacceptable, at least for "well-developed" modern countries like New Zealand. Higher standards are needed, which will result in much lower repair costs, and much less disruption of daily activities after major seismic events.

In order to resolve this major perception gap and dangerous misunderstanding, a twofold approach is required (Pampanin, 2009):

1. On one hand, it is necessary to clearly define, and disclose to the wider public, the targeted performance levels built into building codes (the New Zealand Building Code, and others) including any compromise between socio-economical consequences, on one hand, and technical limitations and costs, on the other. It must be clear that the targeted performance levels are considered "minimum standards", with the possibility of achieving better performance if desired.
2. On the other hand, it is also necessary to significantly "raise the bar" by modifying the New Zealand Building Code, to shift the targeted performance levels from the typically

accepted collapse prevention objective under a severe earthquake, to a fully operational objective. This is represented within the Performance Objective Matrix (Figure 3.5) by a tangible shift of the objective lines to the left, as shown in Figure 3.6. This will require a regulatory move towards higher performance levels (or lower acceptable damage levels).

In order to "raise the bar" two clear solutions are available:

- increase the level of seismic design loading (e.g., increase the Z factor),
- switch to higher-performance building technology.

A combination of these two could be used to guarantee more efficient results.

In this report, more emphasis is given on the latter option (e.g., implementation of higher-performance structural systems and technology for superior seismic protections of buildings).

These changes should apply not only to the structural skeleton, but also to the performance of the whole building system, including non-structural elements and all aspects of building operations.

In the following chapters, an overview of the development of emerging solutions for damage-resisting systems will be given. Some of these are based on base isolation, others on jointed ductile connections, or rocking structural systems, which could rely on the use of unbonded post-tensioned tendons to connect prefabricated elements. Recent examples of site-implementation will be shown for reinforced concrete, structural steel, and timber structures.

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