SEISMIC RETROFIT OF LOW-DUCTILE COLUMNS THROUGH CONCRETE JACKETING WITH INOXYDABLE REINFORCEMENT

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DEDICATION

“Specially Dedicated To…

My Beloved Father, Mother, Wife, daughters, Sisters, and Brothers

Thanks for all the love, support, motivation and always being there

whenever I need you

My Supervisors

Dr. Sophia C. Alih

And

Dr. Mohamadreza Vafaei

For their guidance and assistance throughout the whole thesis”

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ABSTRACT

Retrofit of structures often is an inevitable task especially when buildings are not designed for seismic actions or their design has followed older design codes. Many retrofit strategies have been proposed and practiced by previous researchers. Usage of fiber reinforced polymer [FRP], steel jacketing and reinforcement jacketing are among the most common retrofitting methods. For reinforcement jacketing, carbon steel has been widely employed by engineers, however, only a few applications of inoxydable reinforcements can be found in the literature. Moreover, when it comes to reinforcement jacketing, connection between the interface of original column and the jacket plays an important role and has attracted the attention of many researchers. Load transfer mechanism between original column and jacket is another field of study which has not been addressed in previous research. In this study application of inoxydable rebars for seismic retrofit of Reinforced Concrete (RC) columns was investigated. Two new connectors were used to increase the integrity between the original column and jacket. Load transfer mechanism between original column and jacket is another topic addressed in this research. This study included experimental and numerical analysis. For experimental study, 8 full scale RC columns were constructed and retrofitted with different reinforcement jacketing configurations. Numerical studies investigated the effect of different axial forces on the obtained results from experimental test. Results indicated that regardless of the employed retrofit configurations, the retrofitted columns have higher initial stiffness and ultimate strength compared to un-retrofitted columns. However, the retrofitted columns showed significantly lower ductility ratio when compared with un-retrofitted columns. All the retrofitted columns displayed a brittle failure mode in which spalling of concrete at the base of columns occurred without yield or buckling of reinforcements. Results indicated that confined jackets have higher ultimate strength and stiffness compared to un-confined jackets. However, they showed a lower ductility ratio when compared with un-confined jackets. It was observed that, when internal angle connection was used for retrofit, the highest ultimate strength, post-yield stiffness and effective stiffness were achieved. Monitoring the strain distribution between jackets and original columns revealed that confinement in jackets reduced the strain in the longitudinal reinforcement of original columns more than un-confined jackets. Strain values in the stirrups of confined jackets were significantly smaller than that of un-confined jackets. Strain ratios on the surface of concrete of confined jackets were larger than that of un-confined jackets. It is concluded that the proposed connectors have improved the ultimate strength of retrofitted columns as compared to conventionally retrofitted column, as they were unable to elevate the ultimate strengths to the level of a monolithic column.

ABSTRAK

Pengubahsuaian struktur sering kali merupakan tugas yang tidak dapat dielakkan terutamanya apabila bangunan tidak direka untuk tindakan seismik atau reka bentuknya menggunakan kod reka bentuk yang lebih lama. Banyak kaedah pemulihan struktur telah dicadangkan dan diamalkan oleh penyelidik terdahulu. Penggunaan polimer bertetulang gentian [FRP], pembungkus keluli dan pembungkus tetulang adalah antara kaedah pengubahsuaian yang paling biasa. Untuk pembungkus tetulang, keluli karbon telah digunakan secara meluas oleh para jurutera, bagaimanapun, hanya beberapa aplikasi pembasmian anti-karat yang dapat ditemui dalam kajian terdahulu. Lebih-lebih lagi, untuk kaedah pembungkus bertetulang, hubungan antara tiang dan pembungkus memainkan peranan penting dan telah menarik perhatian ramai penyelidik. Mekanisma pemindahan beban antara tiang dan pembungkus konkrit merupakan salah satu bidang yang masih belum diterokai oleh penyelidik terdahulu. Dalam kajian ini, penggunaan keluli anti-karat untuk pemulihan tiang konkrit berterulang terhadap beban gempa bumi dikaji. Dua jenis penyambung telah digunakan untuk meningkatkan integriti antara tiang dan pembungkus. Mekanisma pemindahan beban antara tiang dan pembungkus konkrit merupakan salah satu topik yang turut dikaji dalam kajian ini. Kajian ini melibatkan kerja-kerja makmal dan analisis berangka. Untuk kajian eksperimen, 8 tiang konkrit berterulang berskala penuh telah dibina dan dipasang dengan konfigurasi pembungkus bertetulang yang berbeza. Analisis berangka mengkaji kesan penggunaan beban paksi yang berbeza terhadap keputusan yang diperolehi daripada kajian makmal. Keputusan kajian menunjukkan bahawa tanpa mengira konfigurasi baik pulih yang digunakan, tiang yang diubahsuai mempunyai kekukuhan awal yang lebih tinggi, kekuatan muktamad dan anjakan berbanding dengan tiang yang tidak diubahsuai. Walau bagaimanapun, tiang yang diubahsuai menunjukkan nisbah kemuluran yang rendah berbanding dengan tiang yang tidak diubahsuai. Semua tiang yang diubahsuai memaparkan sifat kerapuhan di mana pemisahan konkrit pada dasar tiang berlaku tanpa alah atau lengkokan pada tetulang. Keputusan kajian menunjukkan bahawa pembungkus terkurung mempunyai kekuatan dan kekukuhan yang lebih tinggi berbanding pembungkus tidak terkurung. Walau bagaimanapun, ia menunjukkan nisbah kemuluran yang lebih rendah jika dibandingkan dengan pembungkus terkurung. Telah diperhatikan bahawa, apabila sambungan sudut dalaman digunakan untuk kerja pengubahsuaian, kekuatan muktamad yang tertinggi, kekakuan pasca-lengkokan, dan kekakuan berkesan telah dicapai. Pemerhatian terhadap agihan terikan antara pembungkus dengan tiang mendedahkan bahawa pengurungan dalam pembungkus telah mengurangkan terikan dalam tetulang membujur lebih daripada pembungkus tidak terkurung. Nilai terikan pada tetulang pengikat dalam pembungkus terkurung adalah jauh lebih rendah daripada pembungkus tidak terkurung. Nisbah terikan pada permukaan konkrit untuk pembungkus terkurung juga lebih besar daripada pembungkus tidak terkurung. Dapat disimpulkan bahawa penyambung yang dicadangkan telah meningkatkan kekuatan muktamad tiang yang diubahsuai berbanding tiang yang dipasang secara konvensional, kerana penyambung ini tidak dapat meningkatkan kekuatan muktamad ke tahap tiang monolitik.

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LIST OF ABBREVIATIONS

ACI	-	American Concrete Institute
CFTP	-	Carbon Fiber Reinforcement Polymer
FE	-	Finite Element
FEMA	-	Federal Emergency Management Agency
FEM	-	Finite Element Method
FRP	-	Fiber Reinforced Polymer
GFRP	-	Glass Fiber Reinforced Polymer
LVDT	-	Linear Variable Displacement Transducer
RC	-	Reinforced Concrete
SS	-	Stainless Steel
DC L	-	Low Ductility Class
DC M	-	Medium Ductility Class
DC H	-	High Ductility Class
CCDF	-	Conventional Curvature Ductility Factor
HSW	-	High Strength Wire
SCC	-	Consolidating Concrete
LCC	-	Life Cyclic Cost

LIST OF SYMBOLS

A_{stc} - cross section area of the legs in the core and jacket stirrups

A_{stj} - cross section area of the legs in the core and jacket stirrups

$A_{s,req}$ - requirement reinforcement

$A_{s,prov}$ - provisions reinforcement

A_g - gross area of section

A_{st} - total area of longitudinal reinforcement

b_c - gross cross-sectional width

b_o - width of confined core (to the centerline of the hoops)

b_o - minimum dimension of the concrete core

b_i - distance between consecutive engaged bars

C_j - compressive force in the concrete jacket

C_c - compressive force in the concrete core

d_c - distance of the resultant compressive force in the concrete jacket from the neutral axis

D_o - diameter of confined core

d_{bL} - minimum diameter of longitudinal bars

db - reinforcement diameter

d - distance from extreme compression fiber to centroid of longitudinal tension reinforcement

E_c - elastic modulus of concrete

E_{sce} - secant modulus of concrete

F_j - forces in tension steel of the jacket

F'_j - forces in compression steel of the jacket

F_c - forces in tension steel of the core

F'_c - forces in compression steel of the core

f_{ysc} - yield stress of stirrups in the core

f_{ysj} - yield stress of stirrups in the jacket

f_{cu} - stress corresponding to stirrup fracture strain

$f_{c,min}$ - minimum compressive strength of the old or the new concrete in MPa

f_{cc} - maximum principal compressive stress by jacketing

f_{cc} - compressive strength of confined concrete

f_{c0} - strength of unconfined concrete

h_o - depth of confined core (to the centerline of the hoops)

h_c - gross cross-sectional depth

h_c - largest cross-sectional dimension of the column,

h_{cr} - height of the critical region

h_s - clear story height

K - confinement ratio

K_e - effective lateral stiffness

K_i - elastic lateral stiffness of the building in the direction under consideration

K_e - effective lateral stiffness of the building in the direction under consideration

l_{cr} - the length of the critical region

l_{cl} - clear length of the column

n	-	total number of longitudinal bars laterally engaged by hoops or cross ties,
P_{roc}	-	axial strength of RC jacketed column by considering confinement
q	-	behaviour factor
s	-	spacing of hoops
s	-	sliding in mm at the interface
s_{fu}	-	maximum value of sliding at the interface
T_1	-	fundamental period of the building
T_C	-	period of upper limits of the constant spectral acceleration branch
T_i	-	effective fundamental period (in seconds) in the direction under consideration calculated by elastic dynamic analysis
x	-	normalized strain
V_y	-	effective yield strength
α	-	confinement effectiveness factor
$\varepsilon_{sy,d}$	-	design value of tension steel strain at yield,
ε	-	axial strain
ε_{cc}	-	axial strain corresponding to the peak stress in confined concrete
ε_{c0}	-	strain of unconfined concrete
ε_{cc}	-	the strain corresponding to the peak stress, fcc
μ_1	-	coefficient of friction or the initial value of the coefficient of friction when considering cyclic loading
μ_φ	-	required value of CCDF
ν_d	-	normalized design axial force
ρ_s	-	longitudinal reinforcement ratio
ρ_y	-	longitudinal reinforcement ratio at yield conditions

σ_1	-	normal stress at the interface or the initial value of the normal stress at the interface in Mpa
σ_c	-	normal stress at the interface in Mpa
σ_c	-	compressive stress in the concrete
τ_f	-	roughened interface shear stress in Mpa
τ_{fud}	-	ultimate value of the shear stress in Mpa
φ_c	-	concrete resistance factors
φ_s	-	steel resistance factors

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CHAPTER 1

INTRODUCTION

1.1 Introduction

It is well known that many buildings designed based on older codes may be susceptible to severe damage during strong earthquakes. Older buildings have been structurally designed for much lower seismic actions compared to buildings that are designed today. This is because the relevant seismic codes have been continually revised as knowledge about seismic behavior has increased.

Many reinforced concrete frame structures that are built prior to the 1970's were designed for either gravity loads alone, or combination of gravity loads and wind loads. Seismic loads often were not considered in the design of these structures. Reinforcing details used in these structures are now recognized as the cause of low-ductile failure modes under seismic loading. As a result, poor performance of these structures is anticipated and observed under moderate to severe seismic loading.

Columns as structural members that transfer gravity loads to foundations play significant role in structural stability. However, due to the poor reinforcing details, and lack of consideration of seismic loads in the initial design, columns are often found to be vulnerable in low-ductile reinforced concrete structures.

In addition to the above mentioned reasons, column retrofitting are necessary and inevitable due to changes in building's functionality, changes in architectural plans and designs that have not considered forces attributed to collision or explosion.

Jacketing is a method often used to retrofit reinforced concrete columns. Columns may be jacketed through addition of reinforced concrete, steel plates, or various types of fiber reinforced polymer (FRP) materials. Jackets may be used to restore (in the case of damaged or deteriorated columns), maintain, or increase axial load capacity, flexural capacity, and/or shear capacity. Figure 1.1 displays a schematic view of three different retrofit methods for columns. Among retrofit methods of columns, reinforced concrete jacketing has received increasing attention especially for practical application. Low cost, simplicity and reliability are the most important factors for such widespread application in real projects. Figure 1.2 shows some real retrofit cases where RC jacketing is employed for retrofit of columns. Previous studies indicated significant increase in strength and stiffness of retrofitted RC elements through jacketing.

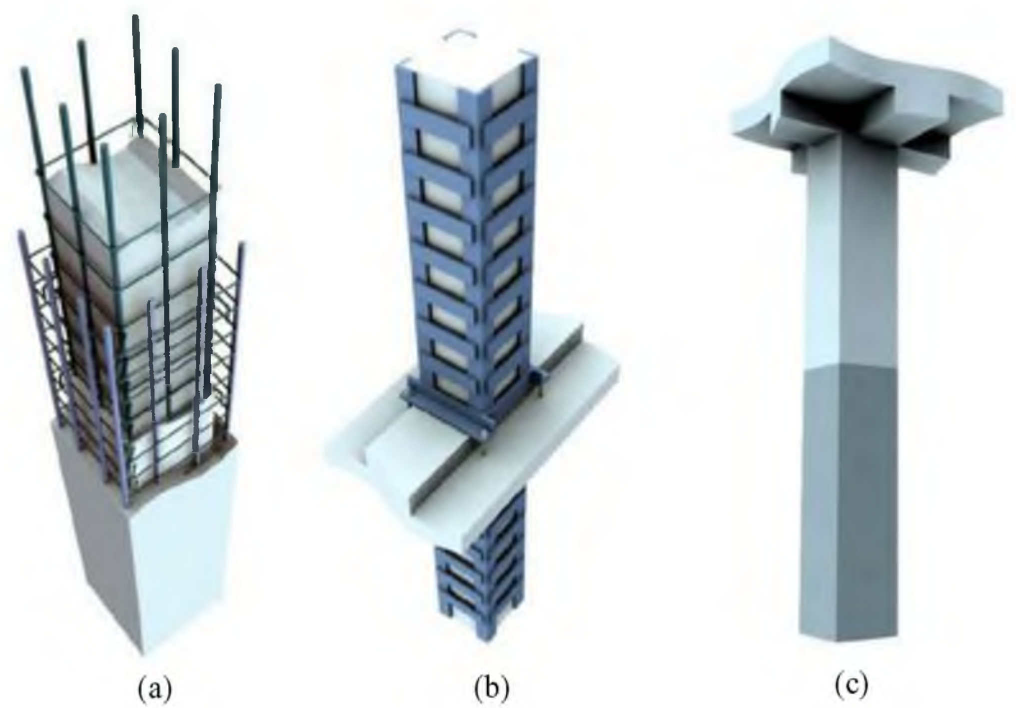

Figure 1.1 Retrofitting methods for columns (a) reinforced concrete jacketing, (b) steel jacketing, (c) FRP wrapping.

(a) (b)

Figure 1.2 Reinforced concrete jacketing; a) jacketing of columns and beams (Sabu and Pajgade, 2012), b) jacketing of columns and foundations (ENUICA et al.)

In spite of advantages that RC jacketing offers, application of this retrofit strategy has privilege for normal environmental condition. Conventional carbon steel used in reinforcing bars is a corrodible material, therefore, in a harsh environmental condition, like piers of bridges or columns constructed inside sea water undergoes a rapid decay. One solution to this problem is the usage of inoxydable rebars that can resist against corrosion even under a harsh environmental condition.

Despite having higher strength and higher ductility compared to the conventional carbon steel, the usage of inoxydable steel for jacketing has not yet being explored. In fact, the application of this type of reinforcement is still new in the construction industry and limited study has been conducted. It is noteworthy that so far conducted research on RC jacketing (Dritsos, et. al., 1997; Julio, et. al., 2003; Júlio, et. al., 2005; Kaliyaperumal & Sengupta, 2014; Vandoros & Dritsos, 2008) has only utilized the conventional carbon steel as the longitudinal bars.

In addition to the superior mechanical properties as compared to carbon steel, inoxydable rebar has an inherent anti-corrosion characteristic which priorities its usage for harsh environment (Alih & Khelil, 2012).

Currently, there are six standards used for inoxydable rebar, namely US: ASTM A955/A955M – 03b, France: XP A35-014 France, Denmark: National Standards & Official Admissions DS 13080 & DS 13082, UK: BS6744: 2001, Finland: SFS – 1259, and Germany and Italy codes. In construction works, the inoxydable steel is employed for several reasons. Not only it is resistant to corrosion, but also, it has a high ductility which increases the energy dissipation in cyclic loading cases. The austenitic type of this steel is investigated by researcher in order to identify their behavior as reinforcement bar in composite concrete beam. Various types of inoxydable steel are categorized in regard to thermal treatment and chemical compositions.

This research investigates the cyclic behaviour of retrofitted columns by RC jacketing using inoxydable steel. Ductility, energy dissipation capacity, yield and ultimate load bearing capacity of eight full-scale columns retrofitted with different configuration of connectors between original column and jacket were studied experimentally. Numerical studies were performed in order to investigate the effect of different gravity load on the seismic behavior of the retrofitted columns.

1.2 Problem statement and motivation for research

It can be shown that columns are in need of retrofit when one of the following conditions arises:

1. New structures that may include unsafe columns due to bad workmanship or due to errors in modeling and design. Such cases, although not very frequent, have to be dealt with taking into consideration the need to preserve the shape and size of the column without altering the intended functional use of the structure and at the same time without compromising to the structural integrity and safety of the structure.
2. The need to place additional loads on columns due to the change in building usage, this includes either the permission to add more floors, or the change of the allowed occupational use of the structure. Such changes are known to happen, especially in largely populated area.

3. Aging of old structures due to deterioration of concrete, corrosion of reinforcing steel bars or both, which leads to the loss of strength of columns and the inability to carry design loads. These structures may be of historical or monumental values and could be considered as part of our heritage, or they could be ordinary structures that simply cost less to repair and maintain than to demolish and reconstruct.
4. Occasionally some structures, or part of them, are subjected to accidents, such as fire or a car collision with one or more of the columns in a car park or a highway bridge, which leads to reduction of column carrying capacity.
5. Buildings that have not been designed for seismic load or they have been designed based on older version of current seismic codes.

One popular solution to strengthen RC column is to place jackets around the structural elements. Jackets have been constructed using steel plates, reinforced concrete and fibre-reinforced polymer (FRP) composites.

FRP composites and steel plates are basically applied to increase shear capacity and ductility of column. These methods are very effective in avoiding columns bond failure with insufficiently lapped of longitudinal reinforcement, although, they offer little enhancement to the flexural and axial strength of an element. As well as, in appropriating if there is a requirement of considerable increase in stiffness. For such condition concrete jacketing has the privilege and can satisfy demand for increase in axial and flexural strength. Furthermore, in many countries, where reinforced concrete known as most used material for structures, engineers prefer the strengthening solution of adding new material such as concrete. The reason is engineers are more familiar with this type of construction and availability of local experienced contractors and personnel.

However, one of the beneficial construction practice is placing reinforced concrete jackets and a number of studies have been presented (Dritsos et al., 1997; Julio et al., 2003; Júlio et al., 2005; Kaliyaperumal & Sengupta, 2014; Vandoros & Dritsos, 2008) there are many unresolved matters indicating the usage of RC jacketing. While the main aim of any retrofit method is to increase the structural capacity of elements, durability of the employed technique is also of great importance. One of the major concerns for RC jacketing is the corrosion of employed reinforcing rebars. Almost all of past studies have concentrated on the usage of normal reinforcement (i.e. carbon steel) and less attention has been paid to inoxydable rebars, which are durable for use in harsh environmental conditions like piers of bridges and columns constructed in seawater. Inoxydable rebars have higher yield and ultimate strength and their ductility is often more than normal reinforcements. Therefore, due to difference in the mechanical properties of inoxydable rebars compared to normal rebars, obtained results from past studies may not be applicable for jacketing using inoxydable steel rebars. This implies that, new studies are required to investigate dynamic behavior of RC columns retrofitted by inoxydable reinforcement.

In addition, a review of literature shows that, when it comes to RC jacketing, the load transfer mechanism between the original column and RC jacket has not been well researched. This issue is of great importance especially for retrofitted columns that suffer from inadequate lap splice. One more issue when using concrete jacketing for retrofit is the integrity between the original column and the jacket. An ideal retrofitted column should have axial force and bending moment capacities similar to a monolithic element. However, due to slippage between the body of jacket and original column, retrofitted columns have lower bending moment and axial force capacities compared to original columns. While research and practice engineers have suggested different connector to reduce the slippage rate, still new studies for developing better connectors are needed. Moreover, in this research, new connectors are introduced to increase the bond between the original column and concrete jacket.

1.3 Objectives of the study

The main aim of this study is to investigate dynamic behavior of RC columns retrofitted with inoxydable steel jackets. The main aim of this research is to address the above-mentioned problems through a series of experimental and numerical studies. The specific objectives of this research are as follow:

a) To investigate seismic behavior (i.e. energy dissipation capacity, stiffness degradation and failure mechanism) of low ductile RC columns with inadequate overlap length.
b) To evaluate the effectiveness of inoxydable reinforcement jacketing for seismic retrofit of low ductile RC columns through numerical and experimental studies.
c) To investigate the load transfer mechanism between original low ductile column and the surrounding jacket through and experimental studies.
d) To develop new connectors between original low ductile column and the surrounding jacket and examine their effectiveness through experimental studies.

1.4 Research Scope

The present study focuses on the retrofitting of concrete columns through reinforcement jacketing. Experimental works are conducted on eight full scale columns with the height of 2000mm and cross sectional size of 200mm by 200mm. The compressive strength of concrete used in this study range from 20MP to 30MPa. The yield and ultimate stress of employed ribbed reinforcement bars for 8,10 and 20mm sizes are 508 to 533 N/mm and 598 to 700 N/mm2 respectively. The yield and ultimate stress of inoxydable reinforcement bars used in jackets are 346 and 639N/mm2, respectively; however, the yield and ultimate stress of plain reinforcement bars used in retrofitted column are 371 and 454N/mm2, respectively. Plain reinforcement bars were used for the retrofitted columns. For jackets and foundations ribbed bars were used. In the retrofitted columns, the overlap length of reinforcement was selected based on the recommendation of British standard.

The cyclic loading applied to columns followed the load protocol suggested by the FEMA461. The axial force used in combination with the cyclic load amounted to 100 kN. Inoxydable steel rebars used for jackets were implanted into the foundation using epoxy glue of Hilty Company. The reinforcement bars used in jackets were inserted as per recommendation of Hilty Company. For numerical studies, Ansys software Ver. 16 was employed in this research.

1.5 Significant of the research

This study deals with the retrofit of columns. The outcome of this research can be used to increase the life time of structures and prevent the possibility of sudden collapse due to seismic actions.

In addition, since this study is devoted to the use of inoxydable rebars for the purpose of retrofit, the findings of this research is of great importance for countries like Malaysia in which the environmental condition can easily corrode the normal reinforcement used for the retrofit of columns. This study also elevates our knowledge about dynamic behavior of retrofitted columns. The invented connectors in this study can be also used to improve the seismic behavior of retrofitted columns with inadequate lap splice. Since the application of inoxydable bars in the retrofit of columns has not been researched, this study provides new findings for practical application of inoxydable bar.

1.6 Outline of the Thesis

This thesis consists of six chapters. The organization of this thesis is as below:

Chapter 1 describes an introduction to the work, describes research objectives and the scope of work, and explains significance and motivation of this research.

Chapter 2 presents a literature review on the dynamic behavior of retrofitted structures. The existing retrofit techniques are described in this chapter.

Chapter 3 describes the research methodology which is employed to achieve the defined objectives. It also describes research design procedure. The details of the selected retrofitted columns, performed tests and procedure in the numerical analysis are explained in this chapter.

Chapter 4 presents the obtained results of the proposed retrofit technique for column based on the experimental tests. The failure mechanism of columns, change in the stiffness and ductility of columns before and after retrofitting are explained in this chapter.

Chapter 5 describes a series of numerical analysis used to improve our understanding about dynamic characteristics of retrofitted columns. Calibration of finite element models are presented in this chapter. Moreover, the effect of different axial load on the cyclic behavior of retrofitted columns is presented in this chapter.

Chapter 6 summarizes the work of this thesis. The research finding, contribution of the thesis and the recommendations for future work are also described in this chapter.

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