STRUCTURAL BEHAVIOUR OF AN INNOVATIVE PRECAST COLD-FORMED STEEL FERROCEMENT AS COMPOSITE BEAM

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To My Parents

Faten Ali, Mubarak Alhajri

And

My Wife and Children

Nora, Mubarak Talal, Abdulaziz Talal, Faten Talal and AbulhadiTalal

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ABSTRACT

This research investigates the structural behaviour of simply supported composite beams, in which a ferrocement slab is connected together with cold-formed steel (CFS) beam by means of shear connectors. This system, called Precast Cold- Formed Steel-Ferrocement Composite Beam System, is designed to utilise the composite action between the CFS sections and ferrocement slab where shear forces are effectively transmitted between the beam and slab via shear connectors.CFS sections have been recognized as an important structural element in developed countries, and sustainable construction material for low rise residential and commercial buildings. However, it still is remains as insufficient data and information on the behaviour and performance of CFS as the composite construction in composite action is yet to be established. One limiting feature of CFS is the thickness of this section that makes it susceptible to torsional, distortional, lateral torsional, lateral distortional and local buckling. Hence, a reasonable solution is resorting composite construction of structural CFS section integrated with reinforced concrete deck slab. An efficient and innovative beam system of built-up CFS sections acting compositely with a concrete deck slab has been developed to provide an alternative composite system for floors and roofs in buildings. In this study, ferrocement is an alternative solution as concrete deck of a slab. It is a form of thin reinforced concrete structure, in which a strong cement-sand mortar matrix is reinforced with closely spaced, multiple layers of thin wire mesh or small diameter rods, uniformly dispersed throughout the matrix of the composite. This study mainly comprises three major components; experimental work, theoretical analysis and finite element analysis using ANSYS (version 11). Experimental works involved small-scale and full-scale testing of laboratory tests. The first phase of test program comprised often push-out test specimens and eighteen full-scale CFS-ferrocement composite beam specimens. Push-out tests were carried out to determine the strength and behaviour of the shear transfer enhancement between the CFS and ferrocement.Three types of shear connectors (bolts, self-drilling screws, bar angle) were tested and 2, 4 and 6 layers of wire mesh in ferrocement cold formed were proposed. The expression for predicting the capacity of shear connector in which bolt with 12mm diameter is best to be considered to transfer shear force into steel section-ferrocement slab interface. The second phase of test program comprised of a total of eighteen full-scale simply supported composite beams with variable parameters and tested to failure. The main variables considered in the study are the shape of section (I- and C-section as beam), thickness (2mm, 3mm and 4mm) of the CFS section and number of wire mesh layer (2, 4 and 6 layers). Four points load bending system was used to test the specimens. The plastic analysis results depicted that the ultimate bending capacity of a ferrocement CFS composite beam can be estimated by using conventional equilibrium procedures and the constitutive laws prescribed by Euro codes. The finite element and theoretical model showed agreement with the experimental results based on the moment versus deflection curves of the proposed composite beam system.

ABSTRAK

Penyelidikan ini mengkaji sifat-sifat struktur rasuk rencam disokong mudah, di mana papak ferosimen disambungkan dengan rasuk keluli tergelek sejuk menggunakan penyambung ricih. Sistem ini dikenali sebagai Rasuk Rencam Pratuang Keluli Tergelek Sejuk-Ferosimen, di mana sistem ini direkabentuk supaya daya ricih antara papak dan rasuk dapat diedarkan secara berkesan melalui penyambung ricih. Keluli tergelek sejuk telah dikenali sebagai elemen struktur penting di negara maju dan bahan pembinaan lestari untuk pembinaan bangunan kediaman dan perniagaan ketinggian rendah. Walau bagaimanapun, maklumat berkaitan dengan sifat-sifat keluli tergelek sejuk dalam pembinaan komposit masih kekurangan. Salah satu kekurangan keluli tergelek sejuk adalah ketebalan keratan yang nipis menyebabkan kilasan dan lengkokan mudah berlaku pada keratan. Oleh demikian, salah satu penyelesaian adalah menggunakan pembinaan rasuk rencam yang melibatkan keratan keluli tergelek sejuk diperkukuhkan dengan papak ferosimen. Satu sistem rasuk rencam yang cekap dan inovasi telah dicipta sebagai salah satu pilihan untuk pembinaan lantai bangunan. Dalam kajian ini, ferosimen digantikan sebagai bahan pembinaan untuk papak lantai. Bahan ini dibina dengan menggunakan simen dan pasir diperkukuhkan dengan lapisan wire mesh nipis atau rod kecil, bertaburan sama rata sepanjang matriks komposit. Kajian ini terdiri daripada tiga komponen utama, kerja eksperimen, analisis teori dan analisis unsur terhingga dengan menggunakan ANSYS (versi 11). Kerja eksperimen melibatkan ujian skala kecil dan ujian skala penuh di makmal. Kerja eksperimen fasa pertama mempunyai sepuluh spesimen ujian menolak-keluar dan lapan belas ujian rasuk rencam skala penuh. Ujian menolak keluar bertujuan menetukan kekuatan dan sifat-sifat penyambung ricih antara keluli tergelek sejuk dan ferosimen. Tiga jenis penyambung ricih (bolt, skru gerudi sendiri dan rod) dengan 2, 4 dan 6 lapisan wire mesh ditanam dalam papak ferosimen telah diuji dalam kajian ini. Merujuk kepada keputusan ujian, bolt dengan garis pusat 12mm telah dicadangkan untuk mengedarkan daya ricih antara keluli tergelek sejuk dan ferosimen. Kerja eksperimen fasa dua melibatkan lapan belas ujian rasuk rencam skala penuh dengan pelbagai parameter dan diuji sehingga gagal. Parameter yang dikaji adalah bentuk keratan rasuk (keratan I- dan C-), ketebalan keratan (2mm, 3mm and 4mm) dan bilangan lapisan wire mesh (2, 4 dan 6 lapisan). Sistem lenturan empat titik beban telah digunakan untuk menguji spesimen rasuk rencam. Keputusan analisis plastik menunjukkan bahawa kekuatan lenturan muktamad rasuk rencam boleh dikira dengan menggunakan kaedah keseimbangan selaras dengan Eurocode. Model kaedah unsur terhingga dan kaedah analisis teori menunjukkan persetujuan yang baik dengan keputusan ujian eksperimen.

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λ	=	Slenderness ratio
f_y	=	Strength of the steel section
t	=	Thickness
L	=	Span of beam
F_{shear}	=	Connection force
F_c	=	Longitudinal resultants in the concrete element
Fs	=	Longitudinal resultants in the steel element
M	=	Total resisting moment
z	=	Distance between the center of the concrete and steel element
ε_c	=	Strain of the concrete
ε_s	=	Strain of the steel
slip	=	Slip strain
E_c	=	Modulus of elasticity of the concrete element
E_s	=	Modulus of elasticity of the steel element
A_c	=	Cross-sectional areas of the concrete element
A_s	=	Cross-sectional areas of the steel element
I_c	=	Moments of inertia of the concrete element
I_s	=	Moments of inertia of the steel element
y_c	=	Distances of the lowest fiber and uppermost fiber of the concrete Element, measured from the neutral axis
y_s	=	Distances of the lowest fiber and uppermost fiber of the steel element, Measured from the neutral axis
s	=	Longitudinal slip
u	=	Longitudinal displacement component
A_c	=	Concrete area
n	=	Modular ratio, E_s / E_c

E_s	=	Elastic modulus of structural steel
E_c	=	Elastic modulus of structural concrete
R_s	=	Axial strength of the steel element
R_c	=	Axial strength of the concrete element
R_q	=	Longitudinal shear strength of the shear connector
η	=	Degree of shear connection
Qu	=	Ultimate shear capacity of the stud connector
f'_c or f_{ck}	=	Concrete cylinder compressive strength
f_u	=	Tensile strength of stud material
V_c	=	Shear strength due to concrete pull-out failure
λ_1	=	Factor dependent upon type of concrete (1.0 for normal density concrete, 0.85 for semi-low density concrete, 0.75 for structural low density concrete)
P_{RD}	=	Strength of the stud connector
t_f	=	Flange thickness of channel shear connector
t_w	=	Web thickness of channel shear connector
H	=	Height of the channel
B_e	=	Effective width of composite beam
P_u	=	Ultimate shear resistance
P_{Rk}	=	Characteristic shear resistance
P_{FEM}	=	Finite element method load
δ_i	=	Initial slip
δ_u	=	Slip capacity
δ_{Pu}	=	Slip at ultimate load
M_u	=	Moment capacity
$M_{u,theory}$	=	Predicted plastic moment capacity
I	=	Second moment of area
δ	=	Deflection of the CFS-concrete composite beams
b_c	=	Effective breadth of concrete slab
h_c	=	Depth of concrete slab
D_s	=	Depth of CFS
t_f	=	Thickness of CFS
t_l	=	Lip length of CFS

b_f	=	Width of CFS
R_{shear}	=	Longitudinal shear resistance of the shear connectors
R_{CFS}	=	Resistance of the CFS beam
R_{conc}	=	Resistance of the concrete
δ_c	=	Deflection of the composite beam with full shear connection
δ_o	=	Deflection of the steel beam acting alone
I_{comp}	=	Second moment of area of the composite section
I_g	=	Second moment of area of uncracked section
I_p	=	Second moment of area of cracked section
P	=	Load
$P_{p,exp}$	=	Experimental elastic load
$M_{u,exp}$	=	Experimental ultimate moment
$M_{e,exp}$	=	Experimental elastic moment
$Mu,_{theory}$	=	Theoretical ultimate moment
d_p	=	Depth of PNA
$d_{p,conc}$	=	Depth of PNA in the concrete element
$d_{p,CFS}$	=	Depth of PNA in the CFS element
y_b	=	Depth of ENA
ε_y	=	Yield strain
$f_{cu,mean}$	=	Average concrete strength
$f_{y,mean}$	=	Average CFS strength
L/d	=	Span to depth ratio

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
AISI	American Iron and Steel Institute
ASTM	American Standards for Testing of materials
BS	British Standards
BTTST	Bent-up Triangular Tab Shear Transfer
CM	Chicken Mesh
CFS	Cold-Formed Steel
DSM	Direct Strength Method
FC	Ferrocement
FRP	Fiber Reinforced Polymer
IFS	International Ferrocement Society
IBS	Industrialized Building System
LYLB	Lakkavalli and Liu Bent-up Tab
LVDT	Displacement Transducers
OPC	Ordinary Portland Cement
RC	Reinforced Concrete
SM	Square Mesh
SP	Superplasticizer
USA	United States of America
UTM	University Technology Malaysia
NAS	North American Specification
PNA	Plastic Neutral Axis
EC4	Eurocode 4
CDAS	Control and Data Acquisition System
ENA	Elastic Neutral Axis
NA	Neutral Axis

FEM	Finite Element Method
HRWR	High Range Water Range
SCM	Self Compacting Mortar
SG	Strain Gauge

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CHAPTER 1

INTRODUCTION

1.1 General Appraisal

The use of composite beam in buildings is becoming popular due to the increase in loading capacity and stiffness. The benefits of the composite beam have resulted in significant savings in steel weight and reduce the depth of the beam. To obtain more economical structural design against the cold-formed steel (CFS) beams, composite beam is designed by taking the advantage of incorporating the strength of concrete slab by means of shear connectors. These advantages of composite beam have contributed to its the dominance in the commercial buildings in steel construction industry. The advantages of composite construction have been further extended with the use of ferrocement with possible use as pre-cast composite beam. Composite action is characterized by interactive behaviour between structural steel and concrete components designed to use the best load-resisting characteristics of each material. Steel and concrete composite system, which together resists the entire set of loads imposed on the structure, is generally more efficient in resisting the applied loads.

An illustrative concrete-steel composite cross-section, commonly used in composite beam, is shown in Figure 1, where the concrete carries compressive forces, while steel, a ductile material, carries the tensile forces in the composite unit. For concrete and steel to act compositely, mechanical connections are generally provided in the form of headed shear studs at the interface of the two materials to resist longitudinal shear. Thus, the resulting system is an integrated, strong, safe, and cost-effective composite structure.

The effectiveness of shear connectors at the steel concrete interface is a key element for achieving composite action in composite structural members. For conventional hot-rolled steel composite structures, extensive research has already been carried out (Deierlein, 1988; Viestet et al., 1997) to develop the most efficient and commercially viable shear connectors. Welded headed shear studs are most prominently used in conventional composite structures as shear connectors. Due to the thinness of the CFS sections, welding of shear studs is not viable (Hanaor, 2000); hence, the development of shear connectors for CFS and concrete composite structures is of utmost importance and require further research.

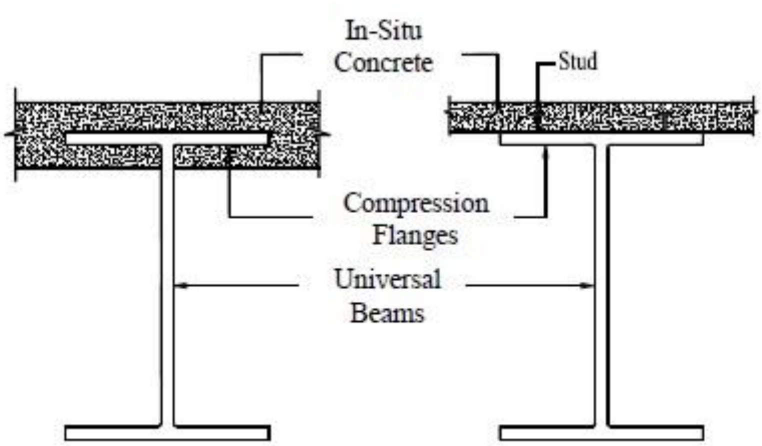

Figure 1.1 Composite Sections

CFS sections are made by bending a flat sheet of steel at room temperature. The use of CFS members in building construction began in the 1850s in both the United States of America (USA) and Great Britain. The CFS structural members have numerous advantages over hot-rolled sections, such as reduced thickness, lightness, ease of prefabrication and mass production, speedy erection, and installation. The use of CFS sections for secondary beams offer many potential advantages, particularly in unusual or special design circumstances. One of the established commercial applications of CFS and concrete is conventional composite beam system, where a concrete topping layer is placed on top of CFS metal deck. However, the structural use of CFS sections began in the mid of 20th century especially for industrial and commercial buildings (Hancock et al., 2001). The typical sections widely used as purlin and truss members are “Z” and “lipped C” sections (Figure 2).

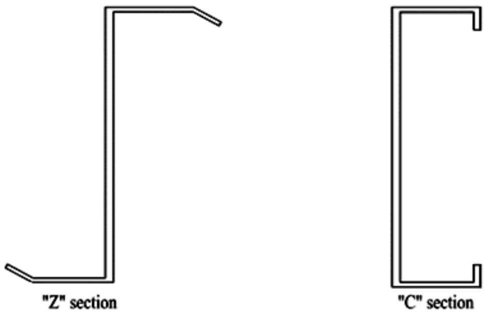

Figure 1.2 Typical CFS sections

Composite construction of CFS sections and concrete began in the mid-1940s in Europe and was mainly used for floor systems, where a steel deck made from CFS was used to act compositely with concrete (Sabnis, 1979).

Ferrocement is a form of thin reinforced concrete structure in which a brittle cement-sand mortar matrix is reinforced with closely spaced multiple layers of thin wire mesh or small diameter rods, uniformly dispersed throughout the matrix of the composite (Naaman, 2000). Ferrocement has taken a significant place among components used for construction, for its specification of durability and strength, and its small thickness, which makes it a component suitable for constructing many lightweight structures. Ferrocement appears to be an economic alternative material for roofing; however flat or corrugated roofing system is quite popular (ACI 549-R97).

This study investigated the structural behavior of composite beam system with CFS as beam and ferrocement as slab. A new shear connector is proposed in this thesis. This type of system could solve the problem of a low flexural bending capacity of the bare CFS as a beam. The proposed composite beam system enhances the flexural capacity and reduces the deflection due to the composite action and also speeds up the construction time as the proposed ferrocement slab acts as permanent formwork.

1.2 Background and Rationale

The construction of industrialized buildings and sustainable houses are in the rise all over the world. In Kuwait, development and construction activity is one of the most important economic activities needed for both the citizens and the huge foreign labor in the state. It has spurred the demand for fast, cost-effective and quality residential buildings. The supply of houses by both the public and private sectors is far from meeting the demand. Rising cost of both building materials and labor is another problem which makes it imperative to study the economic and systematic application of new construction materials and systems.

Industrialization of Building System (IBS) by developing an efficient prefabricated composite structural element may deal with the problem amicably where the fabrication of the elements takes place in factory or workshops and the elements are installed with minimum construction time and minimum number of labor at site.

1.3 Problem Statement

Ferrocement is a thin composite material made up of a cement based mortar matrix reinforced with thin layer of wire mesh closely spaced together. Over the years, applications involving ferrocement have increased due to its properties such as strength, toughness, water tightness, lightness, ductility and environmental stability. The success of ferrocement has been attributed to its a readily available materials components, the low level technology needed for its construction and relatively low cost of final products (ACI 549 R-97).

CFS sections, usually between 1.2 and 3.2mm thickness (Yu et al., 2005), have been recognized as an important contributor to sustainable structures in the developed countries, and a sustainable ‘green’ construction material for low rise residential and commercial buildings. Their usage however, is limited to structural roof trusses and a host of non-structural applications (Shaari and Ismail, 2003). One limiting feature of CFS is the thinness of its section that makes it susceptible to torsional, distortional, lateral torsional, lateral distortional and local buckling. The thinness of CFS is also incapable for CFS-concrete composite beam on the welding of shear studs.

Prefabricated floor is used in the construction sector in many parts of the world. It is an alternative system used to overcome the formwork problems (cost and delay in construction) in addition to getting better quality control. It was found, however, that the prefabricated elements made of reinforced concrete are very heavy and difficult to transport and construct.

In this study, a new type of composite beam comprised of CFS section with ferrocement called Precast Cold–Formed Steel-Ferrocement Composite Beam System is proposed to reduce the weight as well as to enhance the strength of the proposed system. The advantages of this system, amongst others, are its relatively lighter weight as compared to typical reinforced concrete slab which result in the reduction of loading of the supported beams and columns. Key elements for precast system are to stiffen the structure and speed up the construction time. Ferrocement with its versatile properties is the most efficient system available to achieve a light, thin, and stiff structure.

In this study, Ferrocement as slab and CFS as beam are proposed to form a composite structure by means of shear connector. Its properties are also evaluated and compared with other competing materials. The following points reflect powerful properties of CFS and ferrocement which will be integrated together to form a composite action. This will develop the following advantages:

- High strength to weight ratio in behavior for ferrocement and CFS as they are integrated together to form a composite structure.
- A new shear connector is proposed for the proposed composite beam system that works well for precast ferrocement slab and CFS section.

1.4 Aim and Objectives

The main aim of this research is to study the behavior and the properties of an innovative precast proposed ferrocement-CFS composite beam-slab structural system. To achieve this aim, the following objectives are studied:

1. To propose new viable shear connectors for the proposed composite beam system.
2. To study the parameters used that can affect the performance of the proposed composite beam system.
3. To investigate the behaviour and performance of proposed ferrocement slab CFS as composite beam system.
4. To validate the behavior of the proposal composite beam system by Finite Element Analysis (FEA).

1.5 Scope of the Study

A new type of composite beam system is proposed comprising of CFS sections as beam with ferrocement as slab, called Precast Cold–Formed Steel-Ferrocement Composite Beam System. Two types of precast composite beams are proposed, which integrated together the slab system developed from ferrocement with CFS section. This study, however, focuses on the behavior and properties of ferrocement-CFS composite beam-slab structural system. The performance of the proposed shear connector system for the proposed CFS-Ferrocement composite beams is also studied. The scope of the study covers two areas of research work on the proposed CFS–Ferrocement composite action. The first research area is related to the performance of shear transfer. The second research area is related to the performance of the proposed CFS-Ferrocement composite beam.

1.5.1 Push Tests

Ten specimens with different configurations are proposed for the experimental work on push out test for the proposed shear connector. Push-out test method is adopted to study the mode of failure, shear capacity, and ductility due to the changes made to the parameters of the proposed shear connector. Clause 5.4.3 of BS 5950: Part 3 mentioned that since the characteristic resistance value are not presently given in the code for all types of shear connectors other than headed studs; therefore, the characteristic resistance of other types of shear connectors should be determined from push-out test. The strength and ductility of shear connectors are always determined experimentally due to the complexity of the dowel interaction between shear connectors and the concrete slab. The load from the push test is used to determine the shear capacity of each of the proposed shear connector. Details of the experimental test and discussion of results are discussed later in this thesis.

1.5.2 CFS-Ferrocement Composite Beam Tests

The beam section consists of two lipped channels connected back-to-back by 6.3 mm diameter self-drilling and one lipped channel. The flanges were connected with ferrocement panel by three types of shear connectors (Bolts-self-drilling-bar angle). The detail of the specimen description and parameters studied are discussed in Chapter 3.Data from push-out tests was analysed to determine the most viable shear connectors between ferrocement slabs and CFS beams which was then be used in full-scale tests.

The proposed CFS-Ferrocement composite beams were tested as full scale and their results were used to evaluate the behaviour and performance CFS of an I-section was formed by connecting back-to-back of lipped C-channels. There were eighteen specimens with different configurations prepared for full-scale testing. A full-scale of simply supported beam specimens with 4200mm length between supports were tested using four-point load system. The beam was subjected to two point loads with 1400mm measured from the supports. This system of loading produces a constant region of pure bending moment between the two applied loads. Hence, the ultimate flexural capacity of the proposed composite beams can be established. Details of specimens' description and parameters studied are discussed in Chapter 3. The results of the experimental tests were validated by numerical analysis as well as finite element modelling using ANSYS (version 11) software.

1.6 Significance of the Research

Composite beams are extensively used in construction industry due to their efficiency in strength, stiffness and saving materials (Nie et al.,2006; Tahi et al., 2009). To date, headed stud shear connectors are commonly used to perform the composite action between steel beam and concrete slab (Lawson et al., 2001). However, it was found that headed stud shear connectors create a significant tripping hazard on working surfaces at site (US Department of Labor, 2001). Thus, alternative new shear connectors need to be developed. Also, in small and medium size buildings where the span is short (about 4000mm), the use of composite beam with hot rolled steel beam is not effective due to the loss of interaction between steel beam and concrete slab (Johnson, 1981). The proposed composite beams in this study could be an alternative solution to replace the typical composite beam with hot rolled steel and traditional reinforced concrete beams in small and medium size buildings.

Also, in lightweight residential and commercial buildings, CFS members are used as floor beams and joists, and designed as non-composite beams (Popo-Ola et al., 2000; Ghersi et al., 2002). Such beams need to be checked for buckling and most likely failed due to lateral-torsional buckling prior to the attainment of their capacities (Ziemian, 2010). Big steel sections are then used resulting in space and material consuming. Thus, the validation of using CFS sections with ferrocement as a composite beam could significantly increase then strength and stiffness capacities. The ferrocement slab could also provide lateral restrained that prevents the CFS section to fail under lateral-torsional buckling. Also, it could improve the resistance of top flange and reduce its tendency to buckle under compression.

The finding from this research may eventually lead to the development or improvement of the existing system on the welding problem of shear studs on CFS due to its thinness. Therefore, this research is to investigate the possibility of using CFS-ferrocement composite beams for structures. The outcome of this research contributes to promote the proposed composite beam construction method as possible industry implementation and also the use of CFS as one of the alternative materials for small to medium size building construction. Also this research provides important technical knowledge which can be used as a design guideline for the proposed composite beam of CFS and ferrocement structures.

1.7 Thesis Layout

Chapter one presents the general introduction, background of the study, problem statement, aims and objectives and scope of this research. Significance of the study and thesis layout is also described in this chapter.

Chapter two carries a comprehensive literature review on the area of study and all published works related to current study.

Chapter three describes the specimen, test setup and instrumentation used in the experimental for small-scale, push-out test and full-scale flexural test of CFS-ferrocement composite beams.

Chapter four in which three finite element models are used to verify the experimental results and expands the study for more specific points of view.

Chapter five describes the results and analysis of the experimental works for push-out tests and evaluates the strength and behaviour of a shear connector's enhancement.

Chapter six describes the results and analysis of the full-scale flexural test of CFS-ferrocement composite beams.

Chapter Seven presents the discussion and comparison of all the test results, conclusions and the recommendations.

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