A SYSTEMATIC REVIEW: EXPERIMENTAL AND NUMERICAL STUDIES OF FIRE INFLUENCE ON LATERAL RESISTANCE AND BUCKLING PERFORMANCE OF COLD FORMED STEEL SECTIONS

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By

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I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

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(Important Note: This form can only be forwarded to examiners for his/her approval after endorsement has been obtained from the supervisor)

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ABSTRACT

This study presents the review on the critical objectives on the influence of fire on lateral resistance and buckling performance of cold-formed steel (CFS) sections and the methods of conducting the study onto both criteria. More fire safety regulations and countermeasures are needed due to the losses caused by fire events worldwide. Likewise, the use of CFS is expanding recently to industries and mid-rise buildings. This condition required accurate prediction of the buckling behaviour and parameters affecting the lateral resistance of CFS sections in the fire. Even though many studies were related to buckling performance and lateral resistance, they were not discussed directly and clearly. Yet, there are several sections of steel with different effects when exposed to fire. In this review work, it can be observed that the experimental approaches used in this study were described in terms of its specimen preparation, equipment used, and type of test used. On the other hand, the numerical approaches were described in terms of design standards and analysis software used. At last, the influence of fire on CFS sections was discussed.

ABSTRAK

Kajian ini mengemukakan tinjauan mengenai objektif penting mengenai pengaruh kebakaran pada rintangan lateral dan prestasi lengkung bahagian keluli terbentuk sejuk (KTS) dan kaedah menjalankan kajian ke atas kedua-dua kriteria tersebut. Lebih banyak peraturan keselamatan dan penanggulangan kebakaran diperlukan kerana kerugian yang disebabkan oleh kejadian kebakaran di seluruh dunia. Begitu juga, penggunaan KTS berkembang baru-baru ini ke industri dan bangunan pertengahan, keadaan ini memerlukan ramalan tepat mengenai tingkah laku lengkungan dan parameter yang mempengaruhi ketahanan sisi bahagian KTS dalam kebakaran. Walaupun terdapat banyak kajian yang berkaitan dengan prestasi lengkung dan ketahanan sisi, tetapi tidak dibincangkan secara langsung dan jelas. Namun terdapat beberapa bahagian keluli dengan kesan yang berbeza apabila dalam keadaan bakaran. Dalam kajian tinjauan ini, dapat diperhatikan bahawa pendekatan eksperimen yang digunakan dalam kajian ini telah dijelaskan dari segi penyediaan spesimennya, peralatan yang digunakan, dan jenis ujian yang digunakan. Manakala, pendekatan berangka telah dijelaskan dari segi jenis piawai reka bentuk dan perisian analisis yang digunakan. Akhirnya, pengaruh kebakaran pada bahagian KTS telah dibincangkan.

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LIST OF ABBREVIATIONS

CFS	Cold-Formed Steel
USA	United State of America
SLR	Systematic Literature Review
RO	Review Objectives
RQ	Review Questions
LFRS	Lateral Loads Resisting System
QAC	Quality Assessment Criteria
DE	Data Extraction of a form
Q	Question onto the Information Related
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
UK	United Kingdom
RABT	Richtlinien Für Die Ausstattung Und Den Betrieb von Straßentunneln
RWS	Rijkswaterstaat
EC, EN	Eurocode
AS/NZS	Standard Australia and Standard New Zealand
NAS	North American Specifications
AISI	American Iron and Steel Institute
NBR	Brazilian Standard
ASCE	American Society of Civil Engineers
BS	British Standard
ISO	International Organization for Standardization
LVDTs	Linear Variable Displacement Transducers
LWTs	Linear Wire Transducers
ASTM	American Society for Testing Materials
LB	Local Buckling
GB	Global Buckling
TB	Torsional Buckling
LB+TB	Local-Torsional Buckling
FB	Flexural Buckling
FB+TB	Flexural-Torsional Buckling
UCSD	University of California, San Diego

FEA	Finite Element Analysis
FEM	Finite Element Method
PDEs	Partial Differential Equations
cFSM	Constrained Finite Strip Method
DSM	Direct Strength Method
USM	Universiti Sains Malaysia
SHS	Square Hollow Section
RHS	Rectangular Hollow Section
KBS	Keluli Berbentuk Sejuk

LIST OF SYMBOLS

°C	Degree Celsius
S, G, Q	Minimum yield strength of Steel
GD	Grade of Steel
Z	Zinc Coating
P_u	Peak Lateral Load
Δ_y	Yield Displacement
Δ_{85}	Ultimate Displacement when the Lateral Resistance decreased to 85% of Peak Lateral Load

CHAPTER 1

INTRODUCTION

1.1 Background

Cold-Formed Steel (CFS) sections are made from sheet steel that is heated, rolled, pressed, stamped, bent to form several types of the precise shape of sections. The types of shape, for example, are open sections, closed sections, built-up sections, C-sections, Z-sections, the channel I beam, etc. At the same time, no heat is needed to form all those shapes, unlike hot-rolled steel (BuildSteel Org., 2016). CFS can be rolled into a wide range of shapes for both structural and non-structural applications. In lightweight steel constructions, it can be observed that the CFS is becoming a preferred choice. For example, the CFS is used in storage rack systems and roofing systems. CFS's variety of shapes is due to its extraordinary fabrication flexibility. Also, it exhibits a high structural efficiency with its high strength-to-weight ratio. Besides that, CFS has a high production rate, environmental benefits, and flexibility of sectional profiles. CFS is commonly used in both low- and mid-rise structures.

However, in Malaysia and East Asia, the application of CFS is more focused on single-story buildings, with low-rise residential and light industrial construction uses CFS wall frame systems, based on the latest study by Roy et al. (2019). Furthermore, the technology of pre-engineered metal building is starting to grow in the construction of industrial all around the globe. The CFS was first founded in the 1850s in both the United States and the United Kingdom. Its applications are growing in Industrialized Countries like the USA, Canada, Australia, and some European Countries (Billah et al., 2019).

In recent years, CFS sections have become increasingly popular in residential construction and pre-engineered metal buildings for industrial, commercial, and agricultural purposes (Whirlwind Team, 2019). Buckling failure would be the critical failure mode of CFS members due to characteristics such as small open cross-sections and high flexural rigidity variations between two cross-sectional axes (Li & Chu, 2007). Local buckling, global buckling, distortional buckling, flexural buckling, flexural-torsional buckling, and variations of these buckling modes are all examples of buckling modes. In the same context, the lateral deformation is the sideways displacement results from the buckling failure. Since mechanical properties are reduced at the increasing temperatures, lateral deformation and buckling failure are exacerbated when steel parts are exposed to fire (Purkiss & Li, 2013). It is due to CFS's high thermal conductivity, which causes a rapid rise in temperature in a short period (Samiee et al., 2021). Hence, a good fire rating design is required to prevent the unwanted fire from spreading and cause failure.

However, the research on the CFS when exposed to fire is not well documented and wholly covered yet. The behaviour of steel at room temperature has been well known and integrated into current design codes; however, when CFS is exposed to rising temperatures, this is not the case (Maraveas, 2019). Even before, most studies have been based on hot-rolled steel, while those on CFS at increasing temperatures are reduced (Craveiro et al., 2014a, 2016). However, in terms of bending a single CFS member under fire conditions, some necessary research has been conducted using fire furnace experiments and is available in the literature (Cheng et al., 2015b; Kankanamge & Mahendran, 2008; Feng et al., 2003; Laím et al., 2013; Landesmann & Camotim, 2016; Martins et al., 2015).

1.2 Motivation

Generally, when CFS is exposed to heat, its strength and stiffness deteriorate as the temperature rises (Samiee et al., 2021). Also, depending on the load and support conditions, the structure can behave differently in a fire as the temperature rises, just like the research done by Craveiro et al. (2014). Since CFS members have low torsional rigidity and fire resistance, their bearing ability is significantly reduced at high temperatures (Craveiro, 2015; Gunalan et al., 2015).

Nowadays, to expand and widen the application of CFS, some research has been conducted and experimented with testing for the general criteria of the influence of fire on CFS (Laím et al., 2016b). Studying both lateral resistance and buckling behaviour criteria is also necessary to provide safer fire evaluation and fire protection. On the other hand, both criteria are less discussed. However, several papers have mentioned the influence of fire on lateral deformation and buckling resistance, which included sections like lipped and unlipped channel sections, sheathed stud, square hollow sections, storage rack upright, lipped beam, etc., not entirely clear and systematically discussed yet.

Hence, the motivation behind this review work was to perform a systematic review on the influence of fire on lateral resistance and buckling performance of CFS sections.

1.3 Systematic Literature Review (SLR): Review Objectives

This review work will not be focusing on the other related criteria like mechanical properties, material properties, and chemical properties of CFS. The existing research on the respective steel sections is not generalized in their discussion of CFS's buckling analysis and lateral resistance when exposed to fire. Furthermore, there is a lack of research into both criteria, which are buckling behaviour and lateral resistance. In this review, there are different numerical and experimental studies conducted to study CFS's behaviour in the fire. Some analyses will consider the non-uniform and uniform temperature distribution at different temperatures and parts; however, in this review, only non-uniform temperature distribution was studied due to the simulation of a realistic fire condition. How the fire distribution will affect the performance of CFS and their results are the review objectives of this review work.

Therefore, the review objectives of this thesis are as shown in Table 1.1:

Table 1.1: Review Objectives

No.	Review Questions
RO1	To examine the influence of fire on buckling behaviour of CFS sections.
RO2	To examine the influence of fire on lateral resistance of CFS sections.

1.4 Systematic Literature Review (SLR): Review Questions

The SLR includes the following review questions as shown in Table 1.2:

Table 1.2: Review Questions

No.	Review Questions
RQ1	How experimental studies have been conducted to examine the buckling behaviour of cold-formed steel sections in the fire?
RQ2	How experimental studies have been conducted to examine lateral resistance of cold-formed steel sections in the fire?
RQ3	What kind of numerical studies conducted to examine the buckling behaviour of cold-formed steel sections in the fire?
RQ4	What kind of numerical studies conducted to examine lateral resistance of cold-formed steel sections in the fire?

RQ1 was formulated to understand the ways existing experimental procedures were conducted to study the buckling performance of CFS sections in the fire. On the other hand, RQ2 is aimed to investigate the ways of existing experimental procedures conducted to study the lateral resistance of CFS sections in the fire. Next, RQ3 was proposed to provide a deeper understanding of existing numerical methods conducted to investigate the buckling performance of CFS parts in exposure to a fire. Lastly, to recognize the ways of existing numerical studies carried out to examine the lateral resistance of CFS sections in fire, the RQ4 was developed.

1.5 Contribution and Importance

Compared to hot-rolled steel, CFS provides a higher strength-to-weight ratio, more excellent ductility, and faster production and installation (Craveiro, 2015; Gunalan, 2011; Kolarkar, 2011; Niari et al., 2015). However, CFS has high thermal conductivity, which will lead to an increase in temperature in a short time and cause failure. The buckling failure performance and lateral resistance of CFS should be studied more to make the following contributions:

1. Help to identify the experimental approaches in experimenting on CFS in fire conditions.
2. Help to identify the numerical approaches in conducting the numerical modelling on CFS in fire conditions.
3. To know the effect of fire on the buckling behaviour and lateral resistance of CFS sections when exposes to fire.

The typical CFS applications so far, as mentioned by Halabi & Alhaddad (2020), are steel framing systems in low to medium-rise buildings (Lee et al., 2014), composite sections used in conjunction with wood and cementitious materials (Lawson et al., 2008), lateral loads resisting system (LFRS) whereby the shear walls adhered to other sheathing materials, such as gypsum board (Madsen et al., 2016), as well as secondary load-bearing members like purlin, sheeting, girts (Chung & Ip, 2001; Schafer, 2011) and many more. Hence, it is possible to widen the application of CFS in the future, especially in the construction sector.

1.6 Overall Thesis Structure

This thesis was categorized into five chapters. Chapter 1 introduced this study. Next, Chapter 2 provided the systematic literature review protocol in identifying the relevant scholarly sources of the influence of fire on lateral resistance and buckling performance of CFS for review works. Futhermore, in Chapter 3, a systematic literature review (SLR) on 33 past research papers provided a better understanding of the research by evaluating and analyzing the related and existing works. In Chapter 4, the SLR findings concerning each of the four review questions (in Section 1.4) were reported and discussed. Then in Chapter 5, a conclusion and recommendation were made based on the findings.

CHAPTER 2

SYSTEMATIC LITERATURE REVIEW (SLR): A METHODOLOGY

2.1 Introduction to the Systematic Literature Review (SLR)

The primary aim of this proposed research approach is to summarise, classify, and analyze the impact of fire on CFS buckling behaviour and lateral resistance based on numerical and experimental studies that have been conducted. To achieve this goal, a systematic literature review has been proposed. SLR is a method for informing clinical and policy decisions that originated in medical and health science and legislation (Cook et al., 1997; Tranfield et al., 2003). This approach has previously been used to investigate different topics in disciplines such as education (Keating et al., 2017; Perlman et al., 2017), biology (Ansong & Pickering, 2013), sport (Maitland et al., 2015), and business management (Crossan & Apaydin, 2010; Phillips et al., 2015). SLR can identify, evaluate, and select research to address a clearly stated query (Dewey & Drahota, 2016). Transparency, clarity, integration, focus, equality, accessibility, and coverage are the seven central values of SLRs, according to Pittway (2008). The systematic analysis should adhere to a well-defined protocol that explicitly outlines the parameters before the review begins. It is a transparent search that can be replicated and reproduced through different databases.

Thus, the current systematic review focuses on research studies, either experimental or numerical, that have looked at and analyzed the effect of fire on CFS buckling performance and lateral resistance. Transparent and thorough database searches were carried out during the review process to ensure the collection of as many studies as possible on the influence of fire onto both criteria to address the SLR questions.

2.2 SLR Protocol

In doing SLR, no material and equipment are needed; instead, an SLR protocol was conducted step-by-step, as shown in Figure 2.1. The protocol specifies all the steps to be followed by researchers in the review. It will minimize the threats to validity and neutralize the author's bias. One of the key features that distinguish SLR from traditional literature reviews is its review protocol. Thus this protocol is a crucial step in SLR.

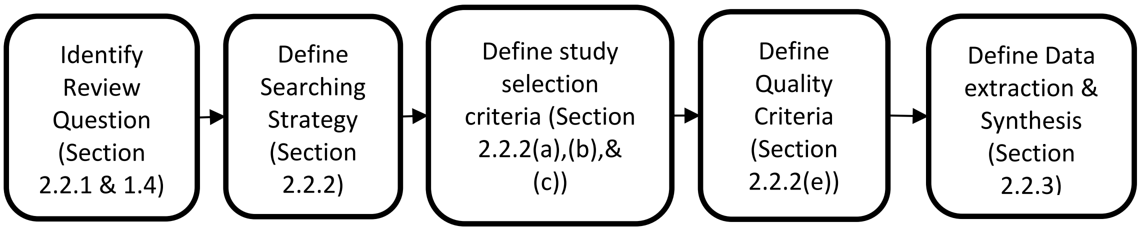

Figure 2.1: SLR Protocol

Firstly, the protocol established the review questions (Section 2.2.1 & 1.4). Next, the searching strategy was defined (Section 2.2.2). Then, the study selection was defined by the criteria inclusion and exclusion (Section 2.2.2(a), (b), (c), & (d)). The quality assessment was conducted (Section 2.2.2(e)). Finally, data from primary studies were collected to answer the review questions (Section 2.2.3). In Chapter 4, the data extracted and synthesized were used to conclude the analysis and discussion conclusion.

2.2.1 Formulation of Review Questions

Counsell (1997) stated that the review question should be well-formulated, answerable, and focused. The review questions defined which study to include, what type of searching strategy to identify the relevant primary studies, and which data is needed to be extracted from each study. A flawed question will result in a poor review. Moreover, a systematic review is based on a pre-defined specific review topic and objectives.

For the study background of this review work, when a steel member is undergoing compression, the subjected load increases until it reaches a critical level, the steel starts to change its shape, then the steel is said to be buckled. There are many types of buckling behavior. One of those is local buckling, which is a widely encountered failure mode in structural steel components. Next, lateral deflection is a sudden sideways deflection of a compression member which results from buckling. The behaviour of structural steel elements at ambient temperatures has been well known and is included in current design codes; however, when such elements are exposed to fire, this is not the case (Maraveas, 2019). The previous research was conducted on hot-rolled steel columns, while those conducted on restrained CFS columns at elevated temperatures were minimal (Craveiro et al., 2014a, 2016).

Further, not many reviews have been conducted on cold-formed steel (CFS) sections in Malaysia. Thus, by conducting a systematic analysis of the literature to give a review work that focuses on investigating the current empirical and numerical studies on buckling behaviour and lateral resistance in CFS sections at the rising temperatures. Thus, the formulated review questions were identified and justified in Section 1.4.

2.2.2 Systematic Searching Strategies

The systematic searching strategies are used in identifying the relevant scholarly sources (previous works) of this review work. Hence, the specific search strings were used to achieve that goal. The following technique and criteria were used to create the search strings used in this review study.

1. Identification: Derive the main keywords from the topics, review objectives, and review questions.
2. Determine the synonyms, related terms, or alternate terms for the main keywords.
3. Check the keywords in all relevant papers the researchers were using, then use them for the initial searches on the relevant databases.
4. Incorporate alternative spelling and synonyms using Boolean “OR”.
5. Link the main terms using Boolean “AND”.
6. Pilot different combinations of the search terms.

Referring to the steps mentioned above, the search string should be defined as below as an example:

(("influence" OR "effect" OR "impact" OR "repercussion" OR "significant") AND("buckling" OR "bending" OR “twisting”)AND("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature"))

Even though there are many digital sources available, but only ScienceDirect and Scopus were used. All of the searched papers were included in the primary studies and are listed in Table 3.2. The authors were contacted by email for papers that were not available online.

2.2.2(a) Identification

Identification is a sub-process of SLR to enrich the keywords related to this study to diverse the searching techniques and find more related and topic-focused articles. Elsewise the database might not detect other plausible articles. Table 2.1 shows the enriched keywords from the title and review questions.

Table 2.1: Identification of Keywords

Section	Main keywords	Enriched keywords
Title: A systematic review for the experimental and numerical studies of the influence of fire on lateral resistance and buckling performance of CFS sections.	Cold-formed steel Influence Fire Lateral resistance Buckling performance	Cold-formed steel = CFS Influence = effect, impact, repercussion, significant Fire = elevated temperature, high temperature Lateral resistance = lateral restraint, lateral Buckling performance = Buckling, buckling behaviour, bending, twisting
RQ1: How experimental studies have been conducted to examine the buckling behaviour of CFS sections in the fire?	Buckling behaviour cold-formed steel Fire	Buckling behaviour = buckling, buckling performance, bending, twisting cold-formed steel = CFS Fire = elevated temperature, high temperature
RQ2: How experimental studies have been conducted to examine lateral resistance of CFS sections in the fire?	Lateral resistance cold-formed steel Fire	Lateral resistance = lateral restraint, lateral cold-formed steel = CFS Fire = elevated temperature, high temperature
RQ3: What kind of numerical studies	Buckling behaviour	Buckling behaviour = buckling, buckling performance, bending, twisting

conducted to examine the buckling behaviour of CFS sections in the fire?	cold-formed steel Fire	cold-formed steel = CFS Fire = elevated temperature, high temperature
RQ4: What kind of numerical studies conducted to examine lateral resistance of CFS sections in the fire?	Lateral resistance cold-formed steel Fire	Lateral resistance = lateral restraint, lateral cold-formed steel = CFS Fire = elevated temperature, high temperature

The databases selected to search the related articles and documents for the review:

i. Leading database: Scopus, ScienceDirect

ii. Supporting databases: NA

2.2.2(b) Screening

Screening is the second sub-process of SLR to filter out the unwanted criteria of the articles and narrow down the scope of searching to get the preferred type of articles wanted by including the favourable criteria. All the criteria were set and known before searching. Generally, the filtering process is based on the timeline, publication type, and language, as shown in Table 2.2.

Table 2.2: Screening Criteria

Criteria	Inclusion	Exclusion
Timeline	2010-2021	Before 2010
Publication type	Review Papers, Research Articles, Journal	Conference proceeding, newspaper, book chapter
Language	English	Non-English
Subject Area	Engineering, Material Science, Chemistry, Structures	Physics & Astronomy, Computer Science

From Table 2.2, the articles from the past ten years were considered. The publication type also considered the review papers to update on the latest existing review status of CFS. Next, only English articles were considered to narrow down the scope and avoid misinterpretation of the content in non-English articles. Finally, the related subject area was also included to filter out the unrelated subjects.

2.2.2(c) Develop Searching Strings

The enriched keywords from Section 2.2.2(a) and the screening criteria set from Section 2.2.2(b) were used to develop the searching strings. Next, follow the searching strategies in Section 2.2.2 to initiate the searching. As the results, Table 2.3 shows the searching strings for the title, and Table 2.4 is for the searching strings of RQ1, Table 2.5 is for the searching strings of RQ2. Additionally, Table 2.6 is for searching strings of RQ3. Then Table 2.7 is for searching strings of RQ4. Overall, the identified synonyms will be linked using Boolean "OR". Thus, the word "influence" was linked with "effect", "impact", "repercussion", and "significant". The word "buckling" was linked with "bending" and "twisting". Then, the word "cold-formed steel" would not be having any synonyms. Next, the term "fire" was linked with "elevated temperature" and "high temperature". Lastly, the term "lateral resistance" was linked with "lateral" only. There is some difference between the searching strings used in both Scopus and ScienceDirect. Firstly, the opening of searching depends on the command on the database, for example, the study field "TITLE-ABS-KEY" as an opening to the searching in Scopus, to search through the title, abstract, and keywords. In contrast, ScienceDirect does not have that requirement in searching. Secondly, the search string length, as in ScienceDirect, limits only eight Boolean connectors per field, which means only four terms maximum per field.

Table 2.3: Searching Strings Developed for Title

Database	Search String
Scopus	TITLE-ABS-KEY(("influence" OR "Effect" OR "impact" OR "repercussion" OR "significant") AND("buckling" OR "bending" OR “twisting”)AND("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature")) TITLE-ABS-KEY(("influence" OR "Effect" OR "impact" OR "repercussion" OR "significant") AND("lateral resistance" OR “lateral”)AND("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature"))
ScienceDirect	("influence" OR "Effect") AND ("buckling" OR ”bending” OR ”twisting”) AND ("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature")) ("influence" OR "Effect") AND ("lateral resistance" OR “lateral”) AND ("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature"))

Table 2.4: Searching Strings Developed for SLR.RQ1

Database	Search String
Scopus	TITLE-ABS-KEY(("influence" OR "Effect" OR "impact" OR "repercussion" OR "significant") AND("buckling" OR "bending" OR “twisting”)AND("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature"))
ScienceDirect	("influence" OR "Effect") AND ("buckling" OR ”bending” OR ”twisting”) AND ("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature"))

Table 2.5: Searching Strings Developed for SLR.RQ2

Database	Search String
Scopus	TITLE-ABS-KEY(("influence" OR "Effect" OR "impact" OR "repercussion" OR "significant") AND("lateral resistance" OR “lateral”)AND("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature"))
ScienceDirect	("influence" OR "Effect") AND ("lateral resistance" OR “lateral”) AND ("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature"))

Table 2.6: Searching Strings Developed for SLR.RQ3

Database	Search String
Scopus	TITLE-ABS-KEY(("influence" OR "Effect" OR "impact" OR "repercussion" OR "significant") AND("buckling" OR "bending" OR "twisting")AND("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature"))
ScienceDirect	("influence" OR "Effect") AND ("buckling" OR "bending" OR "twisting") AND ("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature"))

Table 2.7: Searching Strings Developed for SLR.RQ4

Database	Search String
Scopus	TITLE-ABS-KEY(("influence" OR "Effect" OR "impact" OR "repercussion" OR "significant") AND("lateral resistance" OR "lateral")AND("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature"))
ScienceDirect	("influence" OR "Effect") AND ("lateral resistance" OR "lateral") AND ("cold-formed steel") AND ("fire" OR "elevated temperature" OR "high temperature"))

2.2.2(d) Eligibility

Eligibility was conducted after the selected sources were compiled. The eligibility of the retrieved articles was manually monitored to ensure all the remaining articles (after the screening process) were in line with the criteria. Eligibility can be done by reading the title and abstract of the articles. If there is still no clear understanding gained on the relevance of the selected articles to the study, the article's content needs to be examined.

All procedures involved in systematic searching strategies were then reported using the PRISMA flow diagram (available at http://www.prisma-statement.org/), as in Figure 2.2:

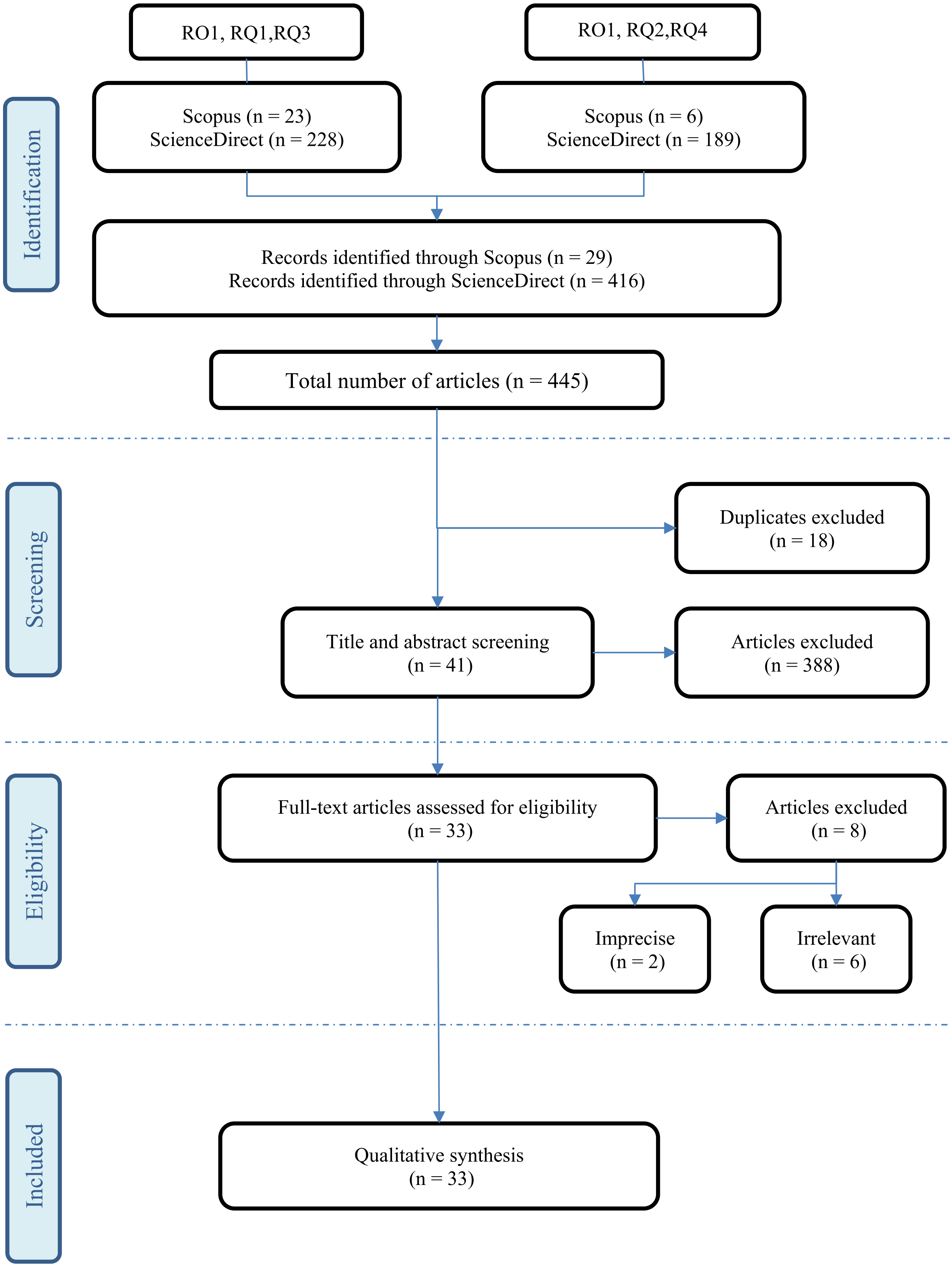

Figure 2.2: PRISMA Flow Diagram

Based on Figure 2.2, the articles from Scopus (n = 29) were less than that of ScienceDirect (n = 416). Yet, the articles that researched the buckling behaviour of CFS (RO1, RQ1, RQ3) with n=23+228=251 are more than the articles that researched the lateral resistance of CFS (RO2, RQ2, RQ4) with n=6+189 =195. It might be because buckling analysis is more common than lateral resistance analysis, regardless of numerical or experimental studies.

The literature retrieved from different initial searches on the digital libraries and a manual search produced 443 primary studies. In the Screening phase, Scopus and ScienceDirect's duplicated sources were removed using the Mendeley Desktop software. At the same time, the irrelevant articles were discarded through reading their abstract by applying inclusion and exclusion criteria adapted from Khan et al. (2003) are listed below:

- Inclusion criteria (IC):

  IC1. The primary research proposes or employs a method to reflect the impact of fire on CFS sections.

  IC2. If several studies were on the same topic, the study's most complete and recent version should be included. However, to increase the understanding and review content, the past and most recent papers were reviewed.

- Exclusion criteria (EC):

  EC1. The primary study addresses the influence of fire on criteria other than buckling performance and lateral resistance of CFS.

  EC2. The lack of sufficient details without describing complete study methods, whether numerical or experimental, in addressing the review questions.

As a result, 41 primary studies were selected to be further reviewed to confirm their eligibility, as shown in table 2.9.

2.2.2(e) Quality Assessment Criteria

In confirming the eligibility, 8 papers were removed for specific reasons and were discussed under this section, and only 33 papers were used for qualitative synthesis. The main reason for removing 8 papers due to irrelevant and imprecise content. Those articles were found when reading through their contents, analysis methods, and tabulation of results.

For the whole quality assessment criteria (QAC), the eligibility questions were formed by referring to the SLR conducted by Caldwell et al. (2011). This article discussed the creation of a framework for critiquing health studies. The framework was designed to be used as a teaching tool and as an aid to an assessment. Thus, in this review work, it was used as an assessment tool.

However, not all questions are being used from the framework since some questions are not relevant to the current review topic, e.g., the question “Is the population identified?” is not being used due to the current topic is not concerning about the human population to get the test sampling and results. Hence, the questions were modified and adapted by referring to the quality assessment strategy defined by (Keele, 2007). In the end, the questions for the QAC with its corresponding objectives are shown in Table 2.8:

Table 2.8: The objectives for the questions of QAC

Number	Question	Objectives
Q1	Does the title reflect the content?	It aims to check the content's reliability or authenticity by referring to the title itself, which is descriptive and allows readers to understand the study's content.

Q2	Are the authors credible?	It aims to verify the reliability of the content through the known authors of the field. For a specific field of study, the expert author or researcher should have a suitable academic qualification related to the professional field applicable to the research.
Q3	Does the abstract summarize the key components?	The abstract's purpose is to verify the content's reliability; the abstract should describe the research's key components, such as the study's goal, methodology outline, and main findings.
Q4	Is the rationale for undertaking the research clearly outlined?	It aims to ensure the author presents a clear rationale for the research and the setting and knowledge in the context of any current issues.
Q5	Is the literature review comprehensive and up-to-date?	It ensures that all relevant aspects of the literature review are addressed simultaneously, ensuring that the literature review is based on the most recent findings, the current state of knowledge relevant to the report, and any gaps or contradictions are found.
Q6	Is the aim of the research clearly stated?	It aims to ensure that the research aims are established and that the setting out to be accomplished by researchers is discussed.
Q7	Is the study design identified and the rationale for the choice of design evident?	It aims to define the study's context and design, such as phenomenology, ethnography, buckling efficiency, or changes in mechanical properties of CFS under fire conditions, to be rationally addressed and determine if the study's design is sufficient to meet the study's objectives.
Q8	Is the concepts/hypothesis clearly defined?	It aims to define and identify the major concepts from the whole article, such that the overall purpose of the study should be clearly stated.
Q9	Is the context of the study outlined?	It aims to ensure that the researcher describes the study's context.
Q10	Is the method of data collection valid and reliable?	It aims to ensure that the data collection methods are described clearly for numerical methods. The type of software and design limitations should be stated, whereas, for the experimental methods, the experiment procedure should be appropriately described.
Q11	Is the method of data analysis valid and reliable?	It aims to ensure that the data analysis strategy is to identify what processes or methods are used to identify the patterns and themes.
Q12	Are the results presented in a way that is appropriate and clear?	It aims to ensure that the presentation of data is clear for the data synthesis later.

As summarised in Table 2.9 below, the 8 articles removed from the review were explained. The first paper was the one that studied the buckling analysis of CFS channel section beams at elevated temperatures (Cheng et al., 2015a).

The second paper is the one that studied the buckling analysis of partially protected cold-formed steel channel section columns at raised temperatures (Cheng et al., 2015b). The first and second papers covered significant enough on the design parts;

however, they did not define the concept of the experiment, in the case that the grade of steel and design standards were not mentioned clearly. Thus, they have been labelled as ‘imprecise’ and excluded from the primary studies. The third paper was by Laím et al. (2020), researching the experimental analysis of CFS columns with intermediate and edge stiffeners in the fire. It has been categorized as ‘irrelevant’ because its focus and discussions were mainly on the edge stiffeners rather than CFS. Fourthly, the paper by Roy, Ting, Lau, & Lim (2019) that investigated the axial capacity of CFS steel built-up box sections is categorized as ‘irrelevant’ due to its main discussion on the mechanical properties of steel. The fifth paper by Liu et al. (2019) that studied the behaviour of square steel tube confined reinforced concrete stub columns is irrelevant to this review work due to its study on hot-rolled ribbed rather than CFS. The sixth paper by Piloto et al. (2017) have experimented with the bending test of partially encased beams is categorized as ‘irrelevant’ due to its study is on hot rolled steel. The seventh paper by Degtyareva et al. (2020a) studied CFS beams' local buckling strength and design with slotted perforations. Lastly, Degtyareva et al. (2020b) studied the new distortional buckling design rules for slotted perforated CFS beams. Both are mainly focused on analysing and discussing slotted perforations than CFS, not under fire conditions, so they were categorized as ‘irrelevant’.

Table 2.9: Eligibility Screening Table

No.	Title	Author	Year	Assessment Criteria												Decision	Category of Exclusion	Reason
				Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12			
1	Analysis and design of cold-formed steel storage rack uprights under localised fires	Ren, Chong Zhang, Peng Yan, Shen Dai, Liusi	2020	√	√	√	√	√	√	√	√	√	√	√	√	√		
2	Behavior of steel-sheathed shear walls subjected to seismic and fire loads	Hoehler, Matthew S. Smith, Christopher M. Hutchinson, Tara C. Wang, Xiang Meacham, Brian J. Kamath, Praveen	2017	√	√	√	√	√	√	√	√	√	√	√	√	√		
3	Behaviour of load bearing double stud LSF walls in fire	Magarabooshanam, Harikrishnan Ariyanayagam, Anthony Mahendran, Mahen	2019	√	√	√	√	√	√	√	√	√	√	√	√	√		
4	Buckling analysis of cold-formed steel channel-section beams at elevated temperatures	Cheng, Shanshan Li, Long Yuan Kim, Boksun	2015	√	√	√	√	√	x							x	Imprecise	The design standard and grade of steel used were not defined.
5	Buckling analysis of partially protected cold-formed steel channel-section columns at elevated temperatures	Cheng, Shanshan Li, Long Yuan Kim, Boksun	2015	√	√	√	√	√	x							x	Imprecise	The design standard and grade of steel used were not defined.
6	Behaviour of restrained high strength steel columns at elevated temperature	Wang, Weiyong Zhang, Linbo Ge, Yong Xu, Lei	2018	√	√	√	√	√	√	√	√	√	√	√	√	√		
7	Cold-formed steel columns made with open cross-sections subjected to fire	Craveiro, Hélder D. Rodrigues, João Paulo C. Laím, Luis	2014	√	√	√	√	√	√	√	√	√	√	√	√	√		

No.	Title	Author	Year	Assessment Criteria												Decision	Category of Exclusion	Reason
				Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12			
8	Collapse behaviour of a fire engineering designed single-storey cold-formed steel building in severe fires	Roy, Krishanu Lim, James B.P. Lau, Hieng Ho Yong, P. M. Clifton, G. C. Wrzesien, Andrzej Mei, Chee Chiang	2019	√	√	√	√	√	√	√	√	√	√	√	√	√		
9	Design of cold-formed steel columns subject to local buckling at elevated temperatures	Rokilan, M. Mahendran, M.	2021	√	√	√	√	√	√	√	√	√	√	√	√	√		
10	Development of improved fire design rules for cold-formed steel wall systems	Gunalan, Shanmuganathan Mahendran, Mahen	2013	√	√	√	√	√	√	√	√	√	√	√	√	√		
11	DSM to predict distortional failures in cold-formed steel columns exposed to fire: Effect of the constitutive law temperature-dependence	Landesmann, A. Camotim, D.	2015	√	√	√	√	√	√	√	√	√	√	√	√	√		
12	Effects of nonlinear elevated temperature stress-strain characteristics on the global buckling capacities of cold-formed steel columns	Rokilan, M. Mahendran, M.	2021	√	√	√	√	√	√	√	√	√	√	√	√	√		
13	Experimental analysis of built-up closed cold-formed steel columns with restrained thermal elongation under fire conditions	Craveiro, Hélder D. Rodrigues, João Paulo C. Laím, Luís	2016	√	√	√	√	√	√	√	√	√	√	√	√	√		
14	Experimental analysis of cold-formed steel columns with intermediate and edge stiffeners in fire	Laím, Luís Craveiro, Hélder D. Simões, Rui Escudeiro, André Mota, Alexandre	2020	√	√	√	√	√	√	x						x	Irrelevant	Experiment with the choice of edge stiffeners
15	Experimental analysis on cold-formed steel beams subjected to fire	Laím, Luís Rodrigues, João Paulo C. Da Silva, Luis Simões	2014	√	√	√	√	√	√	√	√	√	√	√	√	√		
16	Experimental and numerical investigations on the axial capacity of cold-formed steel built-up box sections	Roy, Krishanu Ting, Tina Chui Huon Lau, Hieng Ho Lim, James B.P.	2019	√	√	√	√	√	√	x						x	Irrelevant	Focused on mechanical properties

No.	Title	Author	Year	Assessment Criteria												Decision	Category of Exclusion	Reason
				Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12			
17	Experimental and numerical studies on axially restrained cold-formed steel built-up box columns at elevated temperatures	Yang, Jingjie Shi, Yu Wang, Weiyong Xu, Lei Al-azzani, Hisham	2020	√	√	√	√	√	√	√	√	√	√	√	√	√		
18	Experimental and numerical study on behaviour of square steel tube confined reinforced concrete stub columns after fire exposure	Liu, Faqi Yang, Hua Yan, Rui Wang, Wei	2019	√	√	√	√	√	√	x						x	Irrelevant	The square steel tube uses hot-rolled ribbed
19	Experimental bending tests of partially encased beams at elevated temperatures	Piloto, Paulo A.G. Ramos-Gavilán, Ana B. Gonçalves, Carlos Mesquita, Luís M.R.	2017	√	√	√	√	√	√	x						x	Irrelevant	Not clearly stated the type of steel used. It used hot rolled steel.
20	Experimental study on fire resistance of cold-formed steel built-up box columns	Yang, Jingjie Wang, Weiyong Shi, Yu Xu, Lei	2020	√	√	√	√	√	√	√	√	√	√	√	√	√		
21	Experiments on load-bearing cold-formed steel sheathed studs at elevated temperatures	Batista Abreu, Jean C. Vieira, Luiz C.M. Moreno, Armando Lopes Gernay, Thomas Schafer, Benjamin W.	2020	√	√	√	√	√	√	√	√	√	√	√	√	√		
22	Finite element modelling of load bearing cold-formed steel wall systems under fire conditions	Gunalan, Shanmuganathan Mahendran, Mahen	2013	√	√	√	√	√	√	√	√	√	√	√	√	√		
23	Fire design methodologies for cold-formed steel beams made with open and closed cross-sections	Laím, Luís Rodrigues, João Paulo C.	2018	√	√	√	√	√	√	√	√	√	√	√	√	√		
24	Fire experiments of cold-formed steel non-load-bearing composite assemblies lined with different boards	Chen, Wei Ye, Jihong Li, Xianyong	2019	√	√	√	√	√	√	√	√	√	√	√	√	√		
25	Fire performance of cold-formed steel shear wall with different steel grade and thicknesses	Samiee, Parisa Esmaeili Niari, Shirin Ghandi, Elham	2021	√	√	√	√	√	√	√	√	√	√	√	√	√		
26	Fire performance of cold-formed steel wall panels and prediction of their fire resistance rating	Gunalan, Shanmuganathan Mahendran, Mahen	2014	√	√	√	√	√	√	√	√	√	√	√	√	√		