Committee Report: JCI-TC143A

Technical Committee on Comprehensive Verification Methods for Shear Action in Concrete Structures

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Abstract

The shear failure of reinforced concrete structures is a failure mode of great significance for designing safe and rational structures, and the investigation of the shear carrying mechanism and the accuracy increase of the shear strength calculation methods have been considered as major themes of research in the concrete structure field. This technical committee reviewed the results of researches conducted on the shear issues in recent years, and carried out a research study aiming to provide information that will contribute to the enhancement of the methods for verifying shear of reinforced concrete structures. Particularly, the committee organized the design/verification formulas for the shear force, and explored the possibility of establishing a new verification formula in civil and building engineering, and attempted to evaluate the shear failure behavior of concrete structures using nonlinear numerical analysis techniques.

Keywords: Shear force, shear failure, design/verification formulas, nonlinear numerical analysis, and damage evaluation

1. Introduction

After the proposal of Truss theory by Ritter in 1899, active researches have been performed on the shear failure of the reinforced concrete structure both inside and outside of Japan, accompanied by proposals of numerous experimental formulas and semi-theoretical formulas, and numerical analytical studies have been carried out. In Japan, the "JCI Colloquium on Shear Analysis of RC Structures" held by the Japan Concrete Institute in June, 1982 activated the researches in both construction and civil engineering fields. In October, 1983, the "2nd JCI Colloquium on Shear Analysis of RC Structures" was held, and in December, 1984, the "Colloquium on Finite Element Analysis of RC Structures" was held. Japan Society of Civil

Engineers established the "Standard Specifications for Concrete Structures, Design" as a compilation of these efforts in October, 1986, to propose a shear strength calculation method for beam members where the impact of the size effect has been incorporated based on experiments. On the other hand, the Architectural Institute of Japan compiled "Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept (Draft)" in November, 1988, to propose a shear design method that divides the shear resistance mechanism of RC members into the concrete arch mechanism and shear reinforcement, reinfocing bar, truss mechanism, based on the plastic theory. This was followed by studies on shear design/verification formulas, namely macroscopic models, and studies based on numerical analyses using the finite element method. One of them was the "JCI Colloquium on Analytical Studies on Shear Design of Reinforced Concrete Structures" held by the Japan Concrete Institute in October, 1989. In October, 1993, the Technical Committee on Applications of Fracture Mechanics to Concrete Structures of the Japan Concrete Institute held a reporting session, where studies on the size effect of the member strength, and studies based on nonlinear numerical analysis employing the concept of fracture mechanics were reported.

A succession of earthquake disasters since the Kobe Earthquake of 1995 has activated researches on the seismic design and retrofiting methods. In recent years, researches on the performance evaluation of deteriorated structures have been activated. Under these situations, there were less opportunities for comprehensive discussion of research results on shear issues of the reinforced concrete structure. For this reason, the committee carried out a research study on macroscopic models for the shear force in civil and building engineering and a research study based on the nonlinear finite element analysis (FEM), aiming to provide information that will contribute to the enhancement of shear design methods and verification methods of the reinforced concrete structure.

Table－1.1: Committee Members

Chairman:	Tadatomo WATANABE (Hokubu Consultant Co., Ltd.)
Vice-Chairman:	Hiroshi KURAMOTO (Osaka University)
Secretary-General:	Shigehiko SAITO (University of Yamanashi)
Secretary:	Kohei NAGAI (The University of Tokyo)
	Koshiro NISHIMURA (Hokkaido University)
	Takeshi MAKI (Saitama University)

Macro-Formula WG	
Chief:	Koshiro NISHIMURA (Hokkaido Univeisity)
WG Member:	Kazushi SADASUE (Hiroshima Institute of Technology)
	Yasuhiko SATO (Hokkaido University)
	Hiroshi SHIMA (Kochi Universty of Technology)
	Kohei NAGAI (The University of Tokyo)
	Hikaru NAKAMURA (Nagoya Univeristy)
	Yo HIBINO (Hiroshima University)
	Ken WATANABE (Railway Technical Research Institute)

FEM-WG	
Chief:	Takeshi MAKI (Saitama Univerisity)
WG Member:	Masato SAKURAI (Akita Prefectural University)
	Suguru SUZUKI (Osaka University)
Communications WG Member:	Satoshi TSUCHIYA (Coms Engineering Co., Ltd)

2. Overview of Activities of Technical Committee

The purpose of this technical committee was to establish a systematic method for verifying shear with clarified application methods and ranges of application by reviewing many shear strength calculation methods scattered for each of the materials used, structural type, failure mode, and actions in the civil and building engineering fields based on a theoretical basis. The committee also attempted to evaluate the issues that are difficult to evaluate with the conventional shear strength calculation methods, for example, issues concerning structures with complicated effects or boundary conditions, and structures exhibiting three-dimensional responses. For this attempt, the committee tackled the development of "the advanced evaluation methods based on material damage" utilizing the latest nonlinear analysis method with advanced numerical models combined with the improved computer processing technology. To tackle these tasks, two WGs: Macro-Formula WG for organizing various types of shear strength calculation methods in the civil and building engineering fields, and for exploring rational design and verification methods; and FEM-WG to elucidate the shear failure behavior of structures using nonlinear analysis techniques were formed.

The approach taken by Macro-Formula WG was to clarify the theoretical background and range of application of the past macro formulas in civil and building engineering. The WG particularly examined the effects of various kinds of parameters of sectional dimensions, boundary conditions, failure modes, shear reinforcing methods, etc., and explored expanding the range of application of the macro formulas. It also explored the possibility of establishing new macro formulas based on a mechanism by using nonlinear numerical analyses.

FEM-WG tackled the elucidation of the mechanism of the shear failure behavior using the nonlinear finite element analysis. It particularly attempted to evaluate the load-carrying behavior of wall members and connections using new damage indicators which can quantify the material damage. The use of nonlinear numerical analysis is expected to facilitate modeling of complicated shapes and actions and understanding of the types, progress processes and other matters of damage, thereby making it possible to enhance verification methods and develop new structural types.

This technical committee comprehensively discussed the shear issues of the reinforced concrete structure through the activities of these two WGs. The outline of the results of the activities of the two WGs is as described below:

3. Overview of Explorations of Macro-Formula WG

3.1 Overview

Macro-Formula WG held discussions and conducted reviews in order to propose calculation formulas across both civil engineering structures and building structures. The major topics for the discussions were as follows:

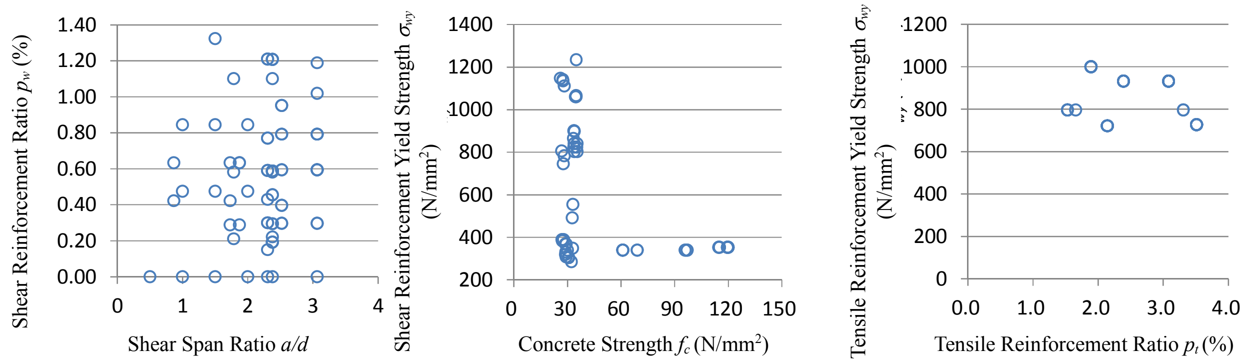
- ✓ Current situations of design formulas in the civil engineering structures and the building structures
- ✓ Reinforcement ratio in the building structures
- ✓ About the types of civil engineering structures and design formulas used
- ✓ Data of RC specimens with rectangular cross-sections under simply supported conditions

- ✓ Shear capacity formulas from the SRC Standards published by the Architectural Institute of Japan[1)]
- ✓ Structural performance and performance evaluation of seismic walls of buildings
- ✓ Researches with FEM on the degree of the contribution of the arch beam (truss) mechanism
- ✓ About the correction of the sear capacity formula of the 1990 AIJ guidelines for reinforced concrete buildings
- ✓ Selection of experimental data (beam members, column members, and wall members)
- ✓ Experimental data specifications and verification using them
- ✓ About the load carrying mechanism of beam members and its modeling

When comparing the members of civil engineering structures with those of building structures, the main differences are: the cross-sections of civil engineering structures are larger than those of building structures, as the heights of the members used in civil engineering reach a few meters; and amount of the reinforcement in building structures, the tension reinforcement ratio of which often exceeds 1.5%, are larger than those in civil engineering structures. Discussions were held also on the relation between different models. The civil engineering and building engineering fields use different words and terms. Macro-Formula WG was discussing the establishment of macro formulas taking these matters into consideration.

3.2 Macro Formulas for Shear Capacity of Members with Rigid Joints at Both Ends

The exploration for establishing macro formulas for shear capacity was done by using, in the initial stages, members with rigid joints at both ends that were subjected to anti-symmetric



(a) Relation between Shear Span Ratio and Shear Reinforcement Ratio

(b) Relation between Concrete Strength and Shear Reinforcement Strength

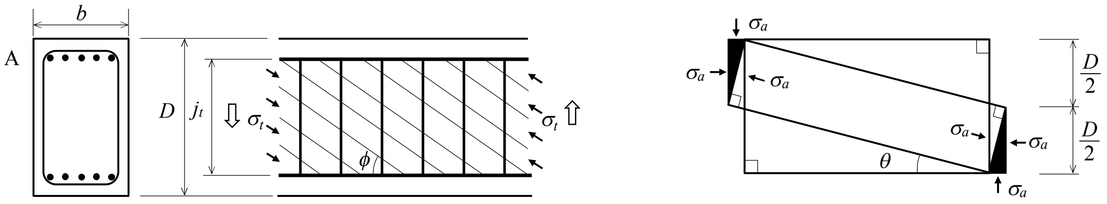
(c) Relation between Tensile Reinforcement Ratio and Tensile Strength

Fig.-3.1: Experimental Data Used for Establishing Macro Formulas (Beams)

bending as standard members. Methods for applying the macro formula for beam members to column and wall members were explored using experimental data.

For establishing macro formulas, experimental data was collected from the past papers. As the primary objects of the experiments done in the civil engineering field are simple supported beams, most of the experimental data was collected from the research reports in the building engineering field. The experimental data was classified into beam members, column members, and wall members (with no opening), and around 100 pieces each of data were collected until now. Fig.-3.1 shows the distribution of the parameters of the beam specimens. The data of beam specimens was collected in a way that the parameters of the shear reinforcement ratio and the shear span ratio are distributed roughly evenly, and the parameters of the concrete strength were added. For column specimens, the parameters of the shear reinforcement ratio and the concrete strength are roughly evenly, and the shear span ratio is around 2. For wall specimens, those for high-strength concrete are limited.

Methods for evaluating the shear ultimate capacity were approached from several viewpoints: one of them is the plasticity theory model employed in the guidelines compiled by the Architectural Institute of Japan. This model adds up the truss mechanism and the arch mechanism shown in Fig.-3.2 and calculates the shear capacity. This WG was seeking to establish calculation methods with which evaluation with high accuracy will be possible also for multi-layer reinforcement, by applying the bond strength formula in the model of "Design Guideline for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept"[2) published by the Architectural Institute of Japan. This is intended for "yield" in the direction of the longitudinal bars of the truss mechanism shown in Fig.3-2. Active discussions were held in WG. For example, some said that this phenomenon did not always indicate a bond splitting failure, and some said that the stress transfer mechanism supposed in the model needed to be clarified so that the comparison with the stress distribution acquired with FEM was possible. Explorations were done, for example, on a method for considering the effect of the axial force as theoretically as possible for column members, and on a method for applying to wall members.



(a) Truss Mechanism (b) Arch Mechanism

Fig.-3.2: Shear Resistance Mechanism in the 1990 AIJ Guidelines for Reinforced Concrete Buildings

3.3 Load Carrying Mechanism with FEM and Shear Capacity Calculation Method for Beam Members

Past studies have already proposed some macro formulas that had been explored on the stress conditions of beam members carrying loads (the load carrying mechanism). Now, the development of nonlinear analysis and experimental technology has facilitated the clarification of this load carrying mechanism more than before. Therefore, the WG quantified the load carrying capacity focusing on beam members for each of the cases when the load is borne by the arch, beam, and truss mechanisms. The results showed that as the axial force and the shear reinforcement bar area increase, the proportions of the loads borne not only by the truss mechanism but also by the arch mechanism increase, and that both simple support and rigid both ends, which are major conditions applied to the building and civil engineering fields, have similar trends of increase, although the effect depends also on the shear span ratio. Based on these findings, Macro-Formula WG was exploring the idea of modeling for deriving macro formulas for calculating the capacity of beam members with no dependence on the support conditions, by clarifying the similarities and differences in the load carrying mechanism.

4. Overview of Explorations of FEM-WG

4.1 Overview

The nonlinear FEM is considered to be effective as a method for elucidating the mechanism of shear failure and evaluating the damage of RC structures and RC members. FEM-WG worked on the establishment of damage indicators for evaluating shear failure of various kinds of RC members using the nonlinear FEM, and on the exploration for methods for evaluating damage using the indicators. To be more specific, FEM-WG explored: the possibility of applying the averaged damage indicators for concrete described in the current Standard Specifications for Concrete Structures, Design[3)] and Standard Specifications for Hybrid Structures, Design[4)] published by Japan Society of Civil Engineers to construction members; more rational verification methods using them; and their applications to the design.

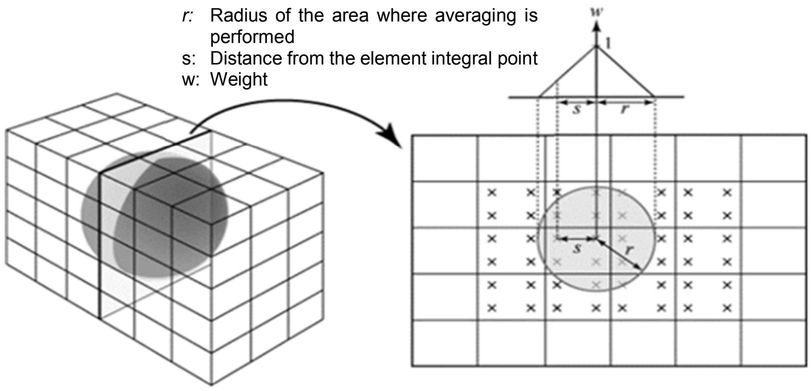


Fig-4.1: Schematic View of Weighted Averaging of Local Damage Indicators[4)]

4.2 Averaged Damage Indicators for Concrete

Indicators to represent the damage of concrete numerically include second invariant of deviatoric strain and normalized cumulative strain energy[5)]. The former is an indicator to represent damage resulting from the tension of concrete such as cracking, and the latter is to evaluate the damage caused by the compression of concrete. However, these index values are calculated based on the local stress and/or strain on the integral points of the finite element, and thus include element dimensional dependence. The weighted averaging processing (Fig.-4.1) in a certain area (a circle in a two-dimensional model, and a sphere in a three-dimensional model) after calculating the local index values on each integral point allows these index values to be used as universal index values with reduced element dimensional dependence. The great feature of the above-mentioned two indicators is that they are non-dimensional scalar quantity, unlike the member axial strain and the principal strain which are directional vector quantity (tensor). It is significantly important that the weighted averaged index values have clear physical meaning.

4.3 Damage Evaluation Using Averaged Damage Indicators

The applicability of the above-mentioned averaged damage indicators to beams, walls, columns, and framed structures of civil engineering structures has already been verified (Fig.-4.2). However, the application of different constitutive equations and the application to building members have not been explored yet. FEM-WG performed numerical investigations using two types of nonlinear FEM analytical codes, by using experiment test specimens for building construction including seismic walls (specimen selected by JCI)[6], seismic walls with openings, and column-beam connections, and explored the applicability of the above-mentioned averaged damage indicators. As a result, it was verified that almost the same evaluation was possible with different analysis codes for all of the targets of the analysis.

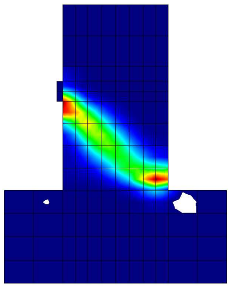


Fig.-4.2: Example of Distribution of Normalized Cumulative Strain Energy of Wall Member Subjected to Horizontal Force

4.4 Application to Design/Verification of Averaged Damage Indicators

The use of these damage indicators will enable clear representation of load carrying mechanisms inside each of the members and clear demonstration of the damage order of members constituting statically indeterminate structures[5]. Also, in view of post-earthquake restoration, for example, it will be possible to quantitatively evaluate the parts, ranges, and degrees of damage in members and structures. From this point of view, the study was expanded into the elucidation of load carrying mechanisms of structures and the verification of the recoverability by linking the changes and distribution of the averaged damage indicators to the damage area of the member. Furthermore, understanding of these matters at the design stage was considered to increase effect and rationality of the reinforcing bar arrangement, etc. The WG also explored a scheme for this.

5. Summary

The shear failure of the reinforced concrete structure is of great significance in designing safe and rational structures. In Japan, there were many colloquiums on shear issues in the 1980s starting from the "JCI Colloquium on Shear Analysis of RC Structures" held in 1982, which led to the investigation of the shear load carrying mechanism of reinforced concrete structures and increase of shear strength calculation accuracy. Many of the current technical standards reflect the results of these studies. After years had elapsed, structures redesigned based on the new technical standards prevented serious damage of earthquake disasters, and this fact is evidence of the usefulness of the results of the studies of that time. However, as the effects of the results of that time were so immediate that they led the misunderstanding that the shear issues have already been resolved. It is also the fact that no innovative explorations have been implemented systematically since then until today. For this reason, this study subcommittee reviewed the results of the researches conducted on the shear issues in recent years, and carried out activities aiming to resolve the issues of that time, and to further enhance the methods for verifying shear of reinforced concrete structures based on the technological evolutions during this period.

As described in the overview of this article, the outcome of this subcommittee is that it gathered a measure of results for the issues left over from the past, and that it gathered views on the direction for the future.

These outcomes published at the shear issue colloquium (held on September 30th, 2016), where discussions focused on shear issues were held.

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