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Dynamic Behavior of Concrete: A Review

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Abstract: Concrete properties are the most essential and critical physical material property when reinforced concrete structures are designed. Considering potential catastrophic accidents, testing of dynamic mechanical properties of concrete is one of the most urgent stages of development. A large number of scientific experiments have shown that the dynamic mechanical properties of concrete are influenced by strain rate. This paper covers the existed researches on the dynamic mechanical characteristics of concrete. Review of the relationship between concrete's dynamic compressive strength, deformation properties, elastic modulus, and energy dissipation capacity with strain rate. The results may vary depending on the loading technique, test apparatus, specimen size, and other variables. The study of dynamic tensile behavior of concrete was uncommon due to the limitations of experimental tools and testing methods. The data returns so far have been inconsistent and even at conflict with one another. The most widely used test techniques to investigate the dynamic tensile behavior of concrete are the direct tensile test, splitting test, bending test and spalling test.
Keywords: Dynamic compressive behavior, Dynamic tensile behavior, Elastic modulus, Deformation properties, Concrete

I. INTRODUCTION

Scientists have been examining the dynamic mechanical properties of concrete since 1917. After nearly a century of research, many scientists have studied the effect of strain rate on the strength, deformation, elastic modulus, and energy consumption of concrete. Currently, several useful research outcomes have been attained. Dynamic compressive properties of concrete are the principal field of study, while tensile properties are studied much less frequently. The dynamic tensile and compressive mechanical characteristics of normal concrete are outlined in this paper.

II. RESEARCH PROGRESS ON THE DYNAMIC COMPRESSION BEHAVIOR OF CONCRETE

A. Strength Properties

Abrams [1]used a lever-type test apparatus for the first time in 1917 to investigate the influence of strain rate on the compressive strength of concrete. It was found that the compressive strength of concrete at a strain rate of 2×10^{-4} s^{-1} was increased by 6% to 20% compared to that at a strain rate of 8×10^{-6} s^{-1}. Since 1960s and 1970s, more and more scientists began to investigate the dynamic compressive strength of concrete using different test equipments over a wide range of strain rates. Ranging from low to high strain rates, the test methods include hydraulic testing, drop-weight test, split Hopkinson pressure bar (SHPB), gas gun test and flat plate impact. Among them, SHPB experiment is a common method used to obtain the dynamic stress and strain relationship of concrete at intermediate strain rates (10^1-10^2 s^{-1}), as shown in Fig. 1. A large number of studies have been performed to investigate the strain rate sensitivity of concrete using SHPB. Bhargava [2] tested the dynamic compressive strength of concrete at a strain rate of 30 s^{-1}, and found that was 1.45 times higher than their static strength. Malvern [3, 4] performed SHPB tests on concrete at a strain rate of 59~118 s^{-1}. It was found that the compressive strength was increased by 74%~120% compared to their static strength. At the strain rate range of 20~190 s^{-1}, Ross [5, 6] found that the dynamic strength increased by 20%~85% in comparison to their static state. Dynamic increase factor (DIF_σ) is the ratio of dynamic compressive strength to static compressive strength, which is widely acceptable to describe the strain rate sensitivity of material. Since there was no uniform standard regarding the selection of strain rate so far, the relationship between strain rate and DIF_σ obtained by different researchers have some variation. According to the available experimental data conducted by SHPB, the dynamic compressive strength of concrete is around 3-4 times higher than that of static strength at highest strain rate.

The results of dynamic compression test in concrete reported between 1917 to 1985 were thoroughly summarized by Bischoff [7], as shown in Fig. 2(a). It was found that the dynamic compressive strength of concrete was significantly affected by the strain rate. The overall regularity of the results reported by numerous researchers was fairly consistent, where the DIF_σ increased with the strain rate. However, when the strain rate exceeded 10^{-3} s^{-1}, the data dispersion was rather high. Bischoff [7] mainly attributed this phenomenon to the different concrete strength, where the strain rate sensitivity of concrete reduced with the increase of compressive strength. The other reasons such as mixing ratio, aggregate type and content, curing condition and age, etc., had the minor effect on the DIF_σ.

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The strain rate considered by Bischoff was mainly focused on the 10^{-5}~$10\ s^{-1}$, where only few test data higher than $10\ s^{-1}$. With the rapidly development of SHPB experimental technique in recently years, a number of valuable research results have been achieved in concrete at higher strain rate. Figure 2(b-d) summarizes the tested DIF_σ of concrete reported between 1942 and 2015, and the strain rate ranged from 10^{-5} to $10^{3}\ s^{-1}$. The result showed that the maximum DIF_σ was around 4.0 for concrete. Since only a few studies achieved the DIF_σ higher than 3.0, more work are needed for the dynamic compressive behavior of concrete at higher strain rate.

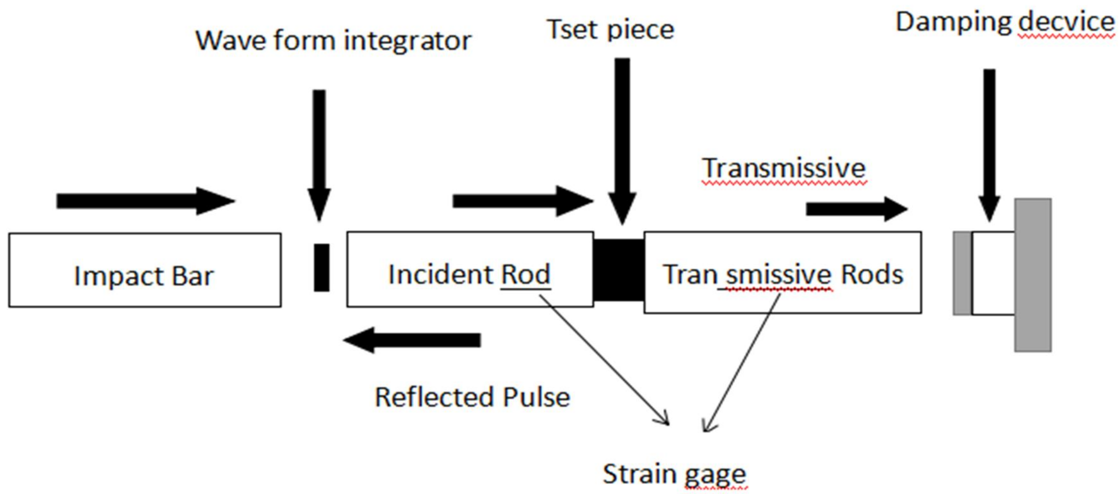

Figure 1 SHPB setup

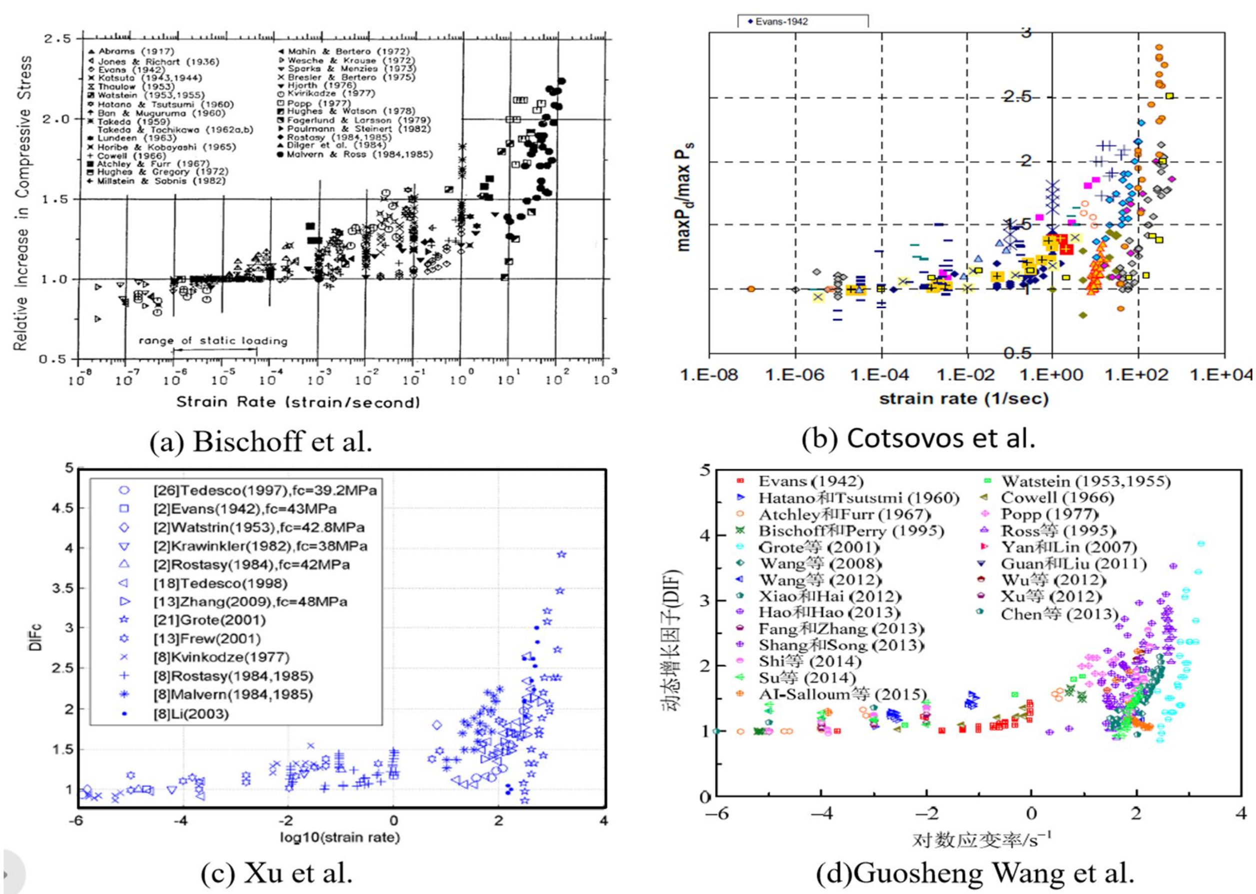

Figure 2 Ratio of dynamic compressive strength to static strength at different strain rates

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Table 2 DIF model for dynamic tensile strength of concrete

source	material	DIF Formula	Parameter definitions
CEB-FIP[8] (1990)	concrete	$\mathrm{DIF}_\sigma=\begin{cases}(\dot{\varepsilon}/\dot{\varepsilon}_s)^{1.026\alpha_s} & \dot{\varepsilon}\le 30\ \mathrm{s}^{-1}\\ \gamma_s(\dot{\varepsilon}/\dot{\varepsilon}_s)^{1/3} & \dot{\varepsilon}>30\ \mathrm{s}^{-1}\end{cases}$ $\mathrm{DIF}_E=(\dot{\varepsilon}/\dot{\varepsilon}_s)^{0.025}$ $\mathrm{DIF}_\varepsilon=\left(\dot{\varepsilon}_d/\dot{\varepsilon}_s\right)^{0.02}$	$\dot{\varepsilon}_s=30\times10^{-6}\ s^{-1}$ $\log\gamma_s=6.156\alpha_s-2$ $\alpha_s=1/(5+9f_c/10)$
Williams et al.[9] (1994)	concrete	$\mathrm{DIF}=1.563\dot{\varepsilon}^{0.059}$	$\dot{\varepsilon}\ge 5\times10^{-4}\ \mathrm{s}^{-1}$
Tedesco et al. (1998)	concrete	$\mathrm{DIF}=\begin{cases}0.00965\lg\dot{\varepsilon}+1.058 & \dot{\varepsilon}\le 63.1\ \mathrm{s}^{-1}\\ 0.758\lg\dot{\varepsilon}-0.289 & \dot{\varepsilon}>63.1\ \mathrm{s}^{-1}\end{cases}$	
source	material	DIF Formula	Parameter definitions
Gebbekenet al.[10] (2000)	SFRC	$\mathrm{DIF}=\left\{\left[\tanh\left(\left(\log\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}-2\right)0.4\right)\right]\left[\frac{F_m}{W_y}-1\right]+1\right\}W_y$	$\dot{\varepsilon}_s=1.0\ \mathrm{s}^{-1}$ $F_m=3.4$ (损伤) $F_m=3.4$ (无损伤) $W_y=(F_m+1)/2$
Groteet al.[11] (2001)	mortar	$\mathrm{DIF}=\begin{cases}0.0235\lg\dot{\varepsilon}+1.07 & \dot{\varepsilon}\le 250\ \mathrm{s}^{-1}\\ 0.882(\lg\dot{\varepsilon})^3-4.48(\lg\dot{\varepsilon})^2+7.22\lg\dot{\varepsilon}-2.64 & \dot{\varepsilon}>250\ \mathrm{s}^{-1}\end{cases}$	
Li et al.[12] (2003)	concrete	$\mathrm{DIF}=\begin{cases}0.03438(\log\dot{\varepsilon}+3)+1 & \dot{\varepsilon}\le 100\ \mathrm{s}^{-1}\\ 1.729(\log\dot{\varepsilon})^2-7.1372\log\dot{\varepsilon}+8.5303 & \dot{\varepsilon}\le 100\ \mathrm{s}^{-1}\end{cases}$	
Lok et al.[13] (2004)	SFRC	$\mathrm{DIF}=\begin{cases}0.017\lg\dot{\varepsilon}+1.080 & \dot{\varepsilon}\le 20\ \mathrm{s}^{-1}\\ 0.796\lg\dot{\varepsilon}+0.067 & 20\ \mathrm{s}^{-1}<\dot{\varepsilon}\le 100\ \mathrm{s}^{-1}\end{cases}$	
Yamaguchi et al.[14, 15] (2007)	concrete	$\mathrm{DIF}=0.2583(\log\dot{\varepsilon})^2-0.05076\log\dot{\varepsilon}+1.021$	
Hao et al.[16] (2013)	SFRC	$\mathrm{DIF}=\begin{cases}A\log\dot{\varepsilon}+B\\ C(\log\dot{\varepsilon})^2-D\log\dot{\varepsilon}+E\end{cases}$	The five parameters vary with the amount of steel fiber

B. Characteristics Of Deformation

The relationships between peak compressive strain of concrete and the strain rate reported by numerous researchers were not consistent. Some researchers reported that the peak compressive strain of concrete decreased with strain rate, and the maximum reduction can be up to 30%. Some other researchers reported the opposite trend, where the peak compressive strain of concrete increased with strain rate and the maximum enhancement can be up to 40%. Other researchers found the peak compressive strain of concrete was insensitive to the strain rate. As shown in Figure 3, Bischoff [7] summarized the relative increase in peak compressive strain at the strain rate range of 10^{-6}~$10\ s^{-1}$. It is evident that three different change trends exist. The curing condition, deformation measuring technique, and specimen loading technique may be the factors occupy for the above phenomenon. With increasing strain rate, Spooner et al.[17] found that the peak strain of concrete cured in a dry environment decreased, while there was no significant change in the peak strain of concrete cured in a humid environment. Watstein et al. [18] observed that the peak strain decreased with increasing strain rate in hydraulic tests, while the opposite phenomenon was observed in drop hammer experiment. The similar conclusion was also observed by Soroushian et al. [19].

Overall, the strain rate sensitivity of peak strain is lower compared to that of concrete strength, and the different testing methods may lead to changes in the variation of peak strain with strain rate. The experimental results presented above are mostly concentrated below 10 s^{-1}. The statistics on dynamic peak strain at higher strain rates are few.

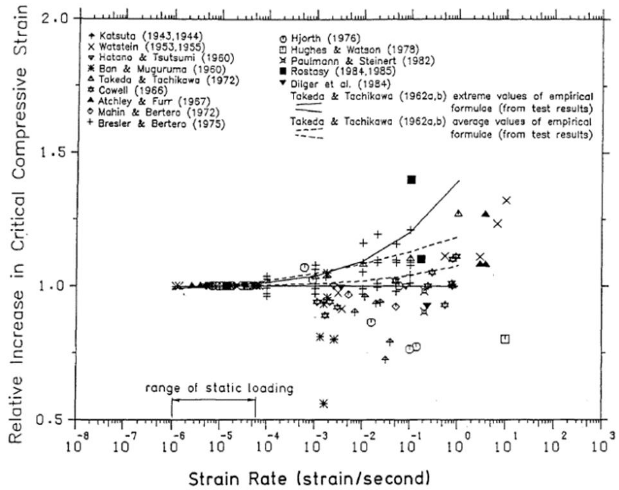


Figure 3 Ratio of dynamic peak strain to static peak strain at different strain rates

The strain measurement of concrete in SHPB test was indirect, which was calculated based on the reflected wave data. In order to directly measure the rising section of the stress-strain curve of concrete, Wu et al. [20] pasted strain gauges on the specimen to measure the strain. Combined with the traditional SHPB data processing method, a more accurate stress-strain curve of concrete under dynamic compressive loading can be obtained. It was indicated that the peak compressive strain increased with increasing strain rate. Under dynamic loading, the simultaneously appearance of a large number of cracks delay the unstable expansion of cracks, which was the reason for the increased peak strain. It was also reported by Zhou et al [21] in the mesoscale numerical simulation of the damage process of concrete under impact loading.

C. Modulus of elasticity

The secant elastic modulus of concrete is the slope of the line between a reference point (1/3 peak stress, failure load or specified axial strain) and the origin point, while the tangent elastic modulus is the slope of the first straight line segment of the stress-strain curve. Based on the currently experimental studies, researchers [22–24] widely accepted that the secant elastic modulus of concrete increased with the increase of strain rate. This is mainly related to the delay in crack extension due to the viscous and inertial effects of concrete under dynamic loading. The stress-strain curve remained linear at higher stress, causing an increase in the secant elastic modulus. However, it is still unclear about the variation of the tangent modulus with strain rate. The results of some researchers showed that the tangent modulus increased with increasing strain rate, while others believe that the tangent modulus was not affected by the strain rate. According to Bischoff et al. [7], the microscopic cracks in the specimen have not yet appeared in the initial linear section, so it is possible that the initial tangent modulus was not affected by the strain rate. Watstein et al [18] performed dynamic compression experiment on concrete with static strengths of 17.4 MPa and 45.1 MPa, respectively. The result indicated that the rate effect of the elastic modulus was more significant in the concrete with lower strength. However, no relationship between strength and elastic modulus rate effect was found in the experiments conducted by Atchley et al.[25] and Sparks et al.[26]. The findings on the dynamic elastic modulus of concrete have not been unified so far, and further experimental studies are needed.

The determination of the dynamic elastic modulus of concrete depends on the accuracy of the rising section of the dynamic stress-strain curve.

In SHPB experiments, the rising section of the stress-strain curve obtained according to the two-wave method is less than ideal because the stress equilibrium state is not reached inside the specimen at the initial stage. Wu et al. [20] obtained a more accurate rising of the stress-strain curve by combining the directly strain measurement method and the traditional SHPB experimental technique. It was found that the nonlinear characteristics of the stress-strain curve of concrete gradually became significant as the strain rate increased. With the increase of the strain rate, the tangent modulus increased obviously while the secant elastic modulus increased slowly. The similar phenomenon was also observed by Lai et al. [27] in UHPC.

D. Energy Consumption Characteristics

The energy absorption capacity of concrete under dynamic loading is related to the strength of the material and its deformation capacity. Most of the current research results showed that the energy absorption capacity of concrete increased with increasing strain rate. Watstein et al.[18]found that the energy absorption capacity of concrete increased by 120% under dynamic loading at a strain rate of about 10 s^{-1}, which was more significant than the increase in dynamic strength. Takeda et al. [28] demonstrated the similar result. When the strain rate reached 1 s^{-1}, the energy absorption capacity of concrete increased by 20%-80%. However, Atchley et al. [25] indicated that the energy absorption capacity of concrete increased by 37-42% when the strain rate reached 3 s^{-1}, which was lower than the increase in strength (about 51%-63%) and gradually approached a constant with increasing strain rate.

III. RESEARCH PROGRESS OF DYNAMIC TENSILE MECHANICAL PROPERTIES OF CONCRETE

Since the limitations of experimental equipment and test methods, the research data of dynamic tensile properties of concrete is relatively rare. The loading method, test equipment, specimen size and some other factors can affect the results. So far, the obtained data results are inconsistent and even contradict each other. Direct tensile test, splitting test, bending test, and spalling test are the commonly used test methods in the existed literatures to explore the dynamic tensile behavior of concrete.

A. Dynamic Direct Tensile Test Of Concrete

Theoretically, the direct tension method is the most suitable method for testing the dynamic tensile properties of concrete. The specimen was fixed on the electro-hydraulic control testing machine through the fixture, and continuously and steadily stretched longitudinally from one end. The dynamic tensile strength, modulus of elasticity, Poisson's ratio and direct tensile stress-strain curve relationship of the material could be obtained directly based on this experiment. The test is conducted under no additional stress, and no conversion of the data is required. At low strain rates, direct tension method is a kind of widely acceptable method to investigate the tensile behavior of concrete-like material. However, at high strain rates, the transfer of stress waves within the specimen will result in the existence of stress and strain gradient fields. It is difficult to ensure that the specimen reaches a state of tensile stress equilibrium before damage, which limit the usage of dynamic direct tensile method.

The first dynamic direct tensile experiment on concrete was performed by Takeda in 1960 [29]. He found that, when the strain rate was 4×10^{-5} s^{-1}, the dynamic tensile strength improved by 55%. Shang et al. [30], Xiao et al. [31] and Yan et al. [32] conducted dynamic uniaxial tensile experiments on a dumbbell-type concrete specimen with a central dimension of 70 mm and a height of 200 mm on an MTS servo fatigue testing machine. The tensile stress-strain relationship, elastic modulus, Poisson's ratio and energy dissipation capacity of concrete at different strain rates were obtained. Shang et al. [30] found that the dynamic tensile strength of concrete at different strain rates (10^{-5} s^{-1}, 2×10^{-4} s^{-1}, 2×10^{-3} s^{-1}, and 2×10^{-2} s^{-1}) were 2.51 MPa, 2.88 MPa, 3.35 MPa, and 3.94 MPa, respectively. The dynamic tensile strength increased by 17% for each order of magnitude increase in strain rate. Xiao [31] studied the uniaxial direct tensile properties of concrete in the strain rate range of 10^{-5}-10^{-2} s^{-1}, and found that the strength increased by 5.7% for each order of magnitude increase in strain rate. With the increase of strain rate, the elastic modulus of concrete increased, but the initial secant elastic modulus, Poisson's ratio and peak strain did not change significantly. The energy absorption capacity could be increased by 4.8%~14.4% with the increase of strain rate. Yan et al. [32] tested the direct tensile properties of C10 and C20 concrete in the range of strain rates from 10^{-5} to $10^{-0.3}$ s^{-1}, and found that the measured growth trend of DIF was slightly higher than that predicted by the CEB recommended equation. With the increase of strain rate, the peak strain of concrete increased and the elastic modulus had an increase of 1.3%-12.1%, while Poisson's ratio remained basically the same. The shape of dynamic stress-strain curves of concrete at different strain rates were similar. The energy absorption capacity of C10 and C20 concrete at $10^{-0.3}$ s^{-1} increased by 68% and 91%, respectively, compared to the static state. As the strain rate increased, more and more aggregates were observed to break in the specimen sections. Ross et al. [33] investigated the effect of moisture contents on dynamic tensile behavior of concrete (with 0% and 100% moisture content). It was found that the strain rate sensitivity in the strength and elastic modulus of wet concrete was higher than that of dry concrete. The tensile strength DIF of dry concrete was 1.4, while the DIF for the wet concrete was 2.1. With the increase of strain rate, the dynamic Young's modulus of dry concrete decreased by 4.5%, while the dynamic Young's modulus of wet concrete increased by 26.6%.

With the development of the Hopkinson technique, the SHTB was introduced to further expand the range of tensile strain rate to 5 s^{-1} [35]. A 51 mm diameter SHTB was utilized by Ross et al. [34, 36] to perform the dynamic direct tensile test on concrete specimens. The specimen was glued on the bar ends, and loaded by separating the two bars through hollow bullet impact. The transverse strain rate for dynamic tension of concrete was 5 s^{-1} and the DIF of tensile strength was 2-4.

Ross et al [34] performed a statistical analysis of the test data on the available literatures, and found that the strain rate effect of tensile strength was higher than that of compressive strength (Figures 1-14).

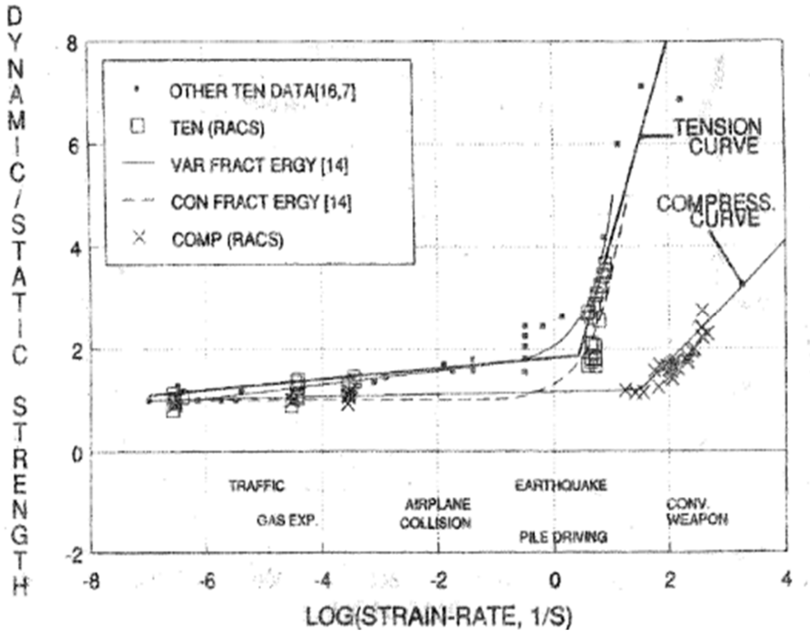


Figure 4 Strain rate in tensile and compressive strength of concrete [34]

Reinhardt et al. [37] investigated the dynamic tensile characteristics of concrete using the SHTB apparatus on Delft University in the Netherlands. Strain gauges on the bar were used to measure the tensile stress, and two LVDTs were put all around the specimen to measure the tensile deformation. The acquired strain rate was between 0.25~1.5 s^{-1}. It was found that tensile strength of dry concrete did not change significantly with increasing strain rate, while there was a significant increase in the DIF of wet concrete. When the tensile strain rate was between 1~1.5 s^{-1}, the DIF of tensile strength for wet concrete ranged between 3-4. Zhang et al. [38] conducted dynamic direct tension experiments using SHTB on concrete with a diameter of 37.5 mm and a height of 75 mm. The specimen was connected to the bar end face by means of a glue-based composite wire wrap. When the tested strain rate ranged from 11.28 to 200.77 GPa/s, the tensile strength increased from approximately 4 MPa to 10.3 MPa. Based on the numerical simulations, it was verified that the tensile rate effect of concrete was found to be independent of the inertia effect.

B. Indirect Tensile Test Results Of Concrete

Operate the direct tensile test method is challenging. Since the eccentric loading and end failure are likely to happen during the test, it is different to test the tensile behavior of concrete using the direct tensile test, especially under dynamic loading. In SHTB test, the bond between the concrete and the bar often occurs at the debonding damage, resulting in the invalidity of the experiment. Therefore, numerous researchers use the indirect tensile test to investigate the dynamic mechanical properties of concrete. dynamic bending test and spalling test are two common indirect tensile test methods. Ren et al. [39] investigated the dynamic bending properties of C40 concrete with dimension of 150×150×550 mm^3 at strain rate of 10^{-6}-10^{-4} s^{-1} using the MTS machine. Compared to the static behavior, the dynamic tensile strength of concrete at the maximum strain rate increased by 24.5% and the dynamic peak strain reduced by 14.9%. In addition, the modulus of elasticity slightly increased, but the Poisson's ratio did not change significantly with the increase of strain rate. You et al. [40] found a 110% increase in tensile strength and a 60% increase in tensile modulus of elasticity for concrete under dynamic bending loading at a strain rate of 0.24 s^{-1} compared to their static behavior.

By using spalling experiments, Mellinger et al. [41] investigated the dynamic tensile characteristics of normal concrete. In the first set of testing, the quasi-static tensile strength was 3.4 MPa at a strain rate of 0.57×10^{-6} s^{-1}, and the dynamic tensile strength was 17.2-22.1 MPa at a strain rate of 20 s^{-1}, with the DIF in dynamic tensile strength of 5.1-6.5. In the second set of experiments, the dynamic tensile strength of concrete was 5.4 to 27.6 MPa at a strain rate of 23 s^{-1}, with the DIF in dynamic tensile strength of 4.5-8.1. Birkimer et al. [42] conducted spalling experiments on concrete with a diameter of 50.8 mm, a length of 889 mm and a static tensile strength of 3.4 MPa at strain rate ranging from 2-23 s^{-1}.

The measured DIF in dynamic tensile strength was 2.5-6, which was linearly related to $\dot{\varepsilon}^{1/3}$. By using close-range blasting, McVay (1988) [43] examined the effects of spalling on the back of concrete wall. At the strain rates of 38 s^{-1} and 157 s^{-1}, DIF in spalling strength of concrete was 7.1 and 6.7, respectively. Zhang et al. [44] utilized SHPB with a diameter of 100 mm to conduct the spalling tests on C30, C60, and C80 concrete with a length of 1600 mm. The corresponding stress rate was 500-1160 GPa/s. The spalling strength of concrete increased with increasing stress rate, and started to decrease when a certain value was exceeded. According to the analysis conducted by Zhang et al., the strain rate effect in spalling strength was mainly related to the damage mode of aggregates in concrete.

After the certain strain rate, the decline in spalling strength was primarily correlated with the damage brought by the compressive stress waves. When normal concrete was subjected to spalling loading, one or more times spalling phenomena can be seen, and the spalling surface entirely fractured.

Therefore, the bending stress measured by the dynamic bending experiment cannot directly reflect the tensile properties of the material. Spalling test is also an indirect test to measure the dynamic tensile strength of concrete, where the tensile wave formed through the reflection of compressive stress wave on the free end face of the specimen. Compared to the standard tensile tests, spalling experiments are more closely related to the damage behavior of concrete under explosion and impact loading. However, it is different from the tensile properties of concrete in the traditional sense.

Splitting test is another common method to test dynamic tensile strength of concrete indirectly, which is simple to operate and easy to fabricate specimens compared to spalling test and bending test. The splitting test is established as a traditional method for evaluating the tensile strength of brittle materials in ASTM C496/C496M-04, the International Society of Rock Mechanics ISRM, the BS1881part4 in British, the JISA1113 in Japan and some other standards. Numerous researchers (Gomez [45], Hughes [46], Ruiz [47], etc.) have demonstrated that the stress distribution in the static splitting specimen is identical to that in the dynamic splitting specimen by using numerical simulation.

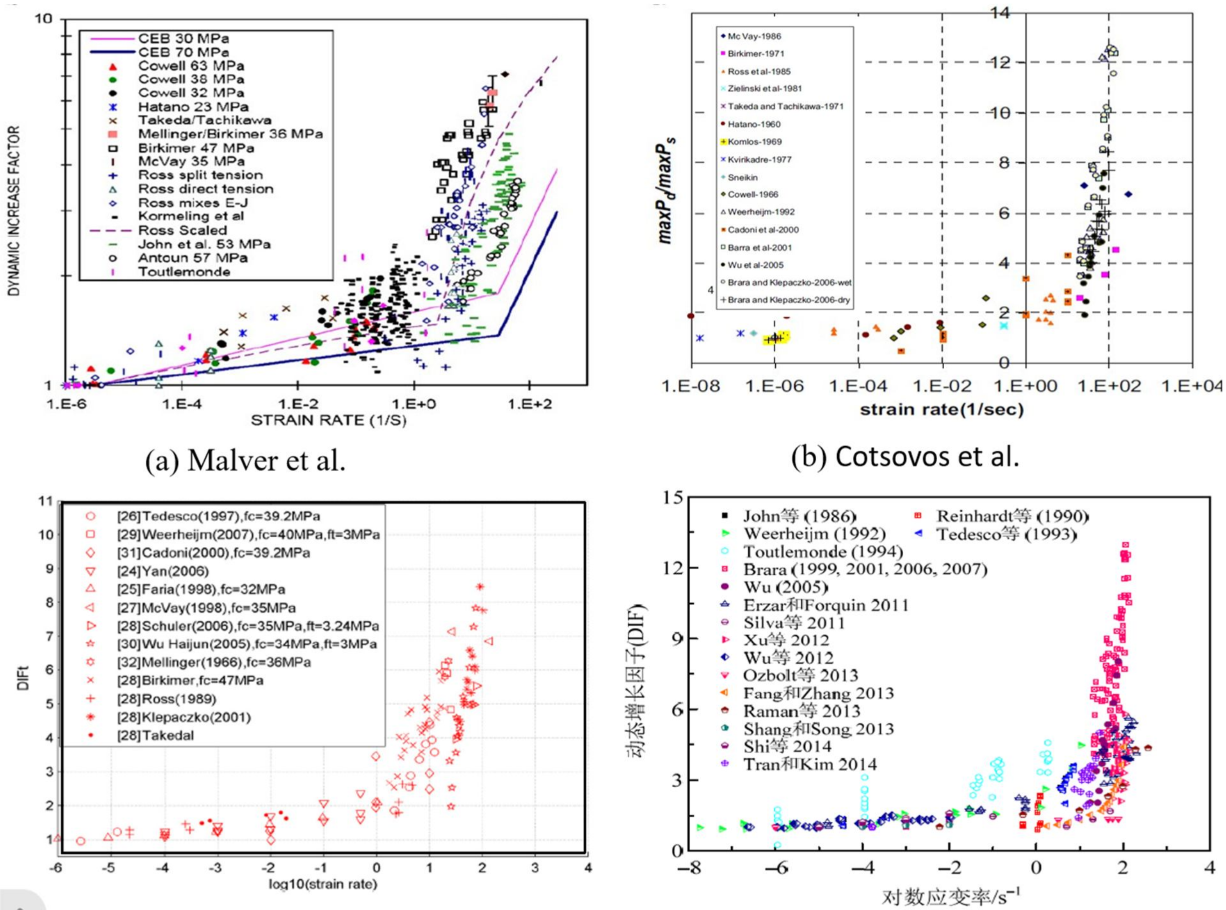
As a result, the static splitting analysis method is equally applicable to the study of dynamic tensile properties of brittle materials. Through experiment and numerical simulation, Wu et al. [48] compared the relationship between the direct tensile, splitting, and flexural strengths of concrete, and found that the direct tensile strength and splitting strength were comparable and lower than the bending strength. The transverse strain rates of the direct tensile and splitting strengths were more similar, which was higher than that of bending strength under dynamic loading. The rate sensitivity of the flexural tensile strength is the highest, the rate sensitivity of the splitting strength is the lowest, and the straight tensile strength is in the middle.

Tedesco et al [49] performed dynamic splitting tests on concrete specimens with a diameter of 50.8 mm and an aspect ratio of 1 using SHPB. The rate sensitivity in splitting strength of concrete started to increase when the strain rate was higher than 1 s^{-1}, and the DIF of concrete was 6.47 at a strain rate of 17.8 s^{-1}. John et al [50] performed dynamic splitting experiments on six series of concrete specimens using SHPB. The dimensions of specimens were 6.4~12.4 mm thickness and 12.7, 25.4, 50.8 mm in diameter at strain rate of 5×10^{-7}~70 s^{-1}.

The tested DIF could reach 4.8. Dynamic splitting tests were performed on cement mortars by Chen et al. [51, 52] with water-cement ratios of 0.4, 0.5, and 0.6 at strain rates ranging from 3 to 12 s^{-1}. The results revealed that the strength of dynamic splitting decreased as the water-cement ratio increased, however, the water-cement ratio had no effect on the dynamic increase factor in splitting strength of concrete.

The study also investigated the dynamic tensile characteristics of cement base, mortar, and concrete at a strain rate of 5~35 s^{-1}. It was found that the dynamic modulus of elasticity, dynamic peak strain, dynamic energy dissipation, and tensile strength of concrete increased with increasing strain rate. Malver et al. [53] summarized the tensile properties of concrete at strain rates of 1-200 s^{-1} based on literatures before 1998, see Figure 1-15. It was found that the strain rate sensitivity of concrete increased significantly when the strain rate exceeded 1 s^{-1}.

When the strain rate reached 157 s^{-1}, the DIF in splitting strength reached 7. Based on the available experimental data, the turning strain rate in the CEB-FIP model for splitting strength was revised from 30 s^{-1} to 1 s^{-1} by Malver et al.. The study also found that the strain rate sensitivity of tensile strength was also related to the compressive strength of concrete. The tensile rate sensitivity of concrete increased with the decreased of compressive strength of concrete. Cotsovos [54], Xu [55] and Wang [56] summarized the results of experimental studies on DIF in dynamic tensile strength of concrete between 1986 and 2016, see Figure 1-14 b-d. The strain rate ranged from 10^{-8} to 10^{2} s^{-1}, and the DIF in dynamic tensile strength of concrete was up to 14. Tables 1-3 and 1-4 list the DIF model for dynamic tensile strength and dynamic compressive strength , respectively, proposed by numerous researchers in this area.



(a) Malver et al.

(b) Cotsovos et al.

(c) Xu et al.

(d)Guosheng Wang et al.

Figure 5 Ratio of dynamic tensile strength to static tensile at different strain rates

Table 2 DIF model for dynamic tensile strength of concrete

source	material	DIF Formula	Parameter definitions
Komlos et al.[57] (1970)	concrete	$\mathrm{DIF}=1+0.1\log\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)$	$\dot{\varepsilon}_s$: Quasi-static strain rate
source	material	DIF Formula	Parameter definitions
Soroushian et al.[58] (1986)	concrete	$\mathrm{DIF}=1.77+0.219\log\dot{\varepsilon}+0.0154(\log\dot{\varepsilon})^2$	
Oh et al.[59] (1987)	concrete	$\mathrm{DIF}=1.95-3.32\left(\frac{1-\dot{\varepsilon}^{1/8}}{2.2+3.2\dot{\varepsilon}^{1/8}}\right)$	
CEB-FIP[8] (1990)	concrete	$\mathrm{DIF}=\begin{cases}\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{1.016\delta} & \dot{\varepsilon}\le 30\ s^{-1}\\ \beta\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{1/3} & \dot{\varepsilon}>30\ s^{-1}\end{cases}$	$\dot{\varepsilon}_s=3\times10^{-6}\ s^{-1}$ $\log\beta=7.11\delta-2.33$ $\delta=1/(10+6f_c/10)$
Reinhardtet al.[60] (1990)	concrete	$\mathrm{DIF}=\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^m$	$\frac{1}{m}=10+\frac{f_{cs}}{2}$

source	material	DIF Formula	Parameter definitions
Malvar et al.[61] (1998)	concrete	$\text{DIF}=\begin{cases}\left(\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{\delta} & \dot{\varepsilon}\le 1\ s^{-1}\\ \beta\left(\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{1/3} & \dot{\varepsilon}>1\ s^{-1}\end{cases}$	$\dot{\varepsilon}_s=10^{-6}\ s^{-1}$ $\log\beta=6\delta-2$ $\delta=1/(1+8f_c/10)$
Tedesco et al.[62] (1998)	concrete	$\text{DIF}=\begin{cases}1+0.1425[\lg\dot{\varepsilon}+5.8456]\ge 1.0 & \dot{\varepsilon}\le 2.32\ \text{s}^{-1}\\ 1+2.929[\lg\dot{\varepsilon}-0.0635]\le 6.0 & \dot{\varepsilon}>2.32\ \text{s}^{-1}\end{cases}$	
Fujikake et al.[63] (2000)	concrete	$\text{DIF}=\exp\left[0.00126\left(\log\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{3.373}\right]$	$\dot{\varepsilon}_s=1\times 10^{-7}$
Lok et al.[64] (2003)	SFRC	$\text{DIF}=0.18\dot{\varepsilon}+1.78$	$9\le\dot{\varepsilon}\le 21\ \text{s}^{-1}$
Yan et al.[65] (2006)	concrete	$\text{DIF}=A\log\left(\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)+1$	C10: A=0.135 C20: A=0.134
Katayama et al.[14] (2007)	concrete	$\text{DIF}=0.4379(\lg\dot{\varepsilon})^2-0.02987(\lg\dot{\varepsilon})+0.8267$	
Zhou et al.[66] (2008)	concrete	$\text{DIF}=\begin{cases}1+0.26[\lg\dot{\varepsilon}+4.0769] & 10^{-4}\le\dot{\varepsilon}\le 1\ \text{s}^{-1}\\ 1+2[\lg\dot{\varepsilon}+0.53] & \dot{\varepsilon}>1\ \text{s}^{-1}\end{cases}$	
Xiao et al.[67] (2008)	concrete	$\text{DIF}=1+0.057\log\left(\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)$	$\dot{\varepsilon}_s=1\times 10^{-5}$ $10^{-5}\le\dot{\varepsilon}\le 10^{-2}$
Xu et al.[55] (2013)	concrete	$\text{DIF}=\left\{\left[\tanh\left(\left(\log\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_s}-1.6\right)0.8\right)\right]\left[\dfrac{10}{W_y}-1\right]+1\right\}W_y$	$W_y=5.5$
Li et al.[68] (2016)	UHTCC	$\text{DIF}=\begin{cases}1+0.03345\log\left(\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right) & 4\times 10^{-6}\le\dot{\varepsilon}\le 10^{-3.29238}\ \text{s}^{-1}\\ 0.75645+0.14912\log\left(\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right) & 10^{-3.29238}<\dot{\varepsilon}\le 10^{-1}\ \text{s}^{-1}\end{cases}$	

IV. SUMMARY

At present, numerous results have been obtained on the study of dynamic compressive mechanical properties of concrete. Several scholars have summarized the relationship between dynamic compressive strength, deformation characteristics, elastic modulus and energy dissipation capacity of concrete with strain rate. However, there are few research results on the dynamic tensile properties of concrete. More work need to be done on this area since the tested data are inconsistent and the conclusions are not really clear.

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