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Research progress on the dynamic compressive properties of ultra-high performance concrete under high strain rates

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ABSTRACT

Ultra-high performance concrete (UHPC) has been accepted rapidly attributed to its superior mechanical performance and the split Hopkinson pressure bar (SHPB) is being widely utilized to evaluate the dynamic compressive properties of UHPC. Numerous studies have been performed on the dynamic behaviour of UHPC, however, a systematic summary and analysis on the dynamic compressive properties of UHPC tested by SHPB is still missing. The review starts by introducing the advantages, deficiencies and improvement methods of SHPB system. Dynamic compressive properties including dynamic compressive strength, peak strain, stress-strain relationship and dynamic elastic modulus are analyzed. The effects of steel fiber (content, type, orientations and hybrid), temperature condition, coarse aggregate, nanomaterials, size effect and loading rate on the dynamic characteristics of UHPC are comprehensively discussed. Dynamic increase factor, energy absorption characteristics and their models are summarized. Then, the dynamic constitutive model and the dynamic failure pattern are evaluated. Based on the analysis, prediction models of dynamic strength and energy absorption are proposed by considering the strain rate and volume of steel fiber, further, a new failure mechanism of UHPC under different strain rates is proposed. Finally, the topics requiring further study are highlighted. It is expected that this paper can provide references for prospective research on dynamic characteristics of UHPC.

1. Introduction

Ultra-high performance concrete (UHPC) often refers to advanced cement-based composite material with very high compressive strength, superior energy absorption capacity and excellent durability [1–5]. Since the first publication of UHPC in the mid-1990s [6], UHPC has experienced vigorous development in recent years. Due to its excellent properties, UHPC can be applied to the military and protective structures subject to impact and explosion loads with high impact velocity [7–9].

A wide range of dynamic loads including seismic, impact, and explosion loads were encountered, ranging in loading speed from low to high. Strain rate regime divisions and the corresponding loading devices are shown in Fig. 1. The current researches demonstrate that UHPC materials under dynamic impact load show significantly different effects from conventional static and quasi-static loads. Strain rate effect is an important reason which makes the dynamic mechanics different from the quasi-static condition. The strength, the crack growth speed, the failure mode, and the energy absorption capacity can be affected by the external loading rate. Buildings and protective projects with UHPC are usually subject to high strain rate impact loads (e.g., vehicle impact, weight fall and blast etc.). Understanding the dynamic behavior of UHPC is crucial for the design and analysis of UHPC structures. Therefore, it is necessary to summarize and deepen dynamic response understanding of UHPC to promote its application and development.

Steel fiber (content, types and orientations), aggregate, temperature condition all have significant effect on dynamic compressive properties. To investigate the influence of the above factors on the impact resistance of UHPC, accurate determination of dynamic compressive properties over a wide range of strain rates is essential. Among the available
researches concerning UHPC, the stress-strain relationship of the tested material can be obtained from the split Hopkinson pressure bar (SHPB) test, from which the dynamic strength, peak strain and energy absorption of the material can be calculated. Therefore, SHPB has been widely applied to investigate dynamic loading with high strain rates, ranging from 10 to $10^4 \text{ s}^{-1}$ [10].

Over decades, the dynamic characteristics of UHPC have been investigated by many researchers with great progress. The experimental principles of compression, Spalling and Brazilian tests applying SHPB, and the strain rate effect of dynamic increase factor (DIF) and numerical simulations on SHPB were briefly summarized by Khosravani and Weinberg [10]. A review on dynamic tensile behavior of UHPC was conducted by Thomas and Sorensen [11]. The dynamic mechanical behaviors such as dynamic compressive, tensile and flexural characteristics of UHPC under impact and blast load were reviewed by Yoo and Banthia [12]. DIF, energy absorption capacity and dynamic constitutive models are important indicators in analysis and design of UHPC structures under impact loadings, and failure pattern mechanism of UHPC can benefit the comprehension of the relationship between indicators and the strain rate. Nevertheless, a comprehension on the dynamic compressive properties including dynamic compressive strength, DIF, peak strain, stress-strain relationship, dynamic elastic modulus, energy absorption capacity, dynamic constitutive models and failure pattern of UHPC tested by SHPB are still missing. The steel fiber content, steel fiber type and strain rates on dynamic compressive characteristics of UHPC are reviewed by Soufeiani et al. [13]. However, other factors concerning steel fibers including fiber orientations and hybridization are not addressed. In addition, influential parameters like temperature condition (low and high temperature), coarse aggregate gradation, nanoparticles and size effect have not been well discussed. Therefore, a comprehensive review on the recent progress of UHPC concerning dynamic compressive properties applying SHPB covering these topics would be of great significance for the future researchers, especially considering the very fast development of this topic in the last years (e.g. about 500 research articles can be found in ScienceDirect with the keywords of UHPC and dynamic properties published in period of 2017–2021, while 66 papers in the same period with the keywords of UHPC and SHPB).

This review aims to present a comprehensive analysis and summary on the dynamic compressive properties of UHPC. The review is organized in the following structure. Firstly, a concise introduction describing the advantages, deficiencies and improvement methods of the SHPB system then the tests on dynamic compression of UHPC by SHPB are summarized. Next, the effect factors such as strain rate, steel fiber (content, types, aspect ratio and hybrid), aggregate size, nanoparticles, size effect and temperature are observed systemically on the dynamic compressive characteristics, including dynamic compressive strength, peak strain, stress-strain curves and elastic modulus. A prediction model of dynamic strength considering strain rate and steel fiber volume is proposed based on the existing literature data in this section. DIF and energy absorption capacity are presented and the associated modelling studies are summarized and compared in Section four. A model for energy absorption is established based on the existing literature. Then, commonly used classic dynamic constitutive models and their modified models are summarized in Section five. Further, in Section six, the dynamic failure pattern and mechanism of UHPC are discussed. Finally, the issues that need to be further addressed and a discussion on prospective research are provided in Section seven.

2. Split Hopkinson pressure bar

2.1. The advantages and deficiencies of SHPB system

As a commonly utilized device to quantify the dynamic mechanic response of various brittle materials, such as ceramic [14], concrete [15, 16], rocks [17, 18] and restorative dental composites [19]. The SHPB device mainly consists of a loading apparatus, bar system, and data recorder, as schematically illustrated in Fig. 2. The detailed theory of the SHPB test can be referred to the literature [20–22]. Compared to the swinging pendulum test, drop weight test, and blast test, the stress-strain relationship of the tested material can be obtained precisely by the SHPB test, from which the dynamic strength, peak strain and energy absorption of the material can be calculated [23]. However, some limitations and deficiencies of SHPB test still exist when testing concrete materials [24]. During SHPB tests, inertia effects and friction effects can lead to inaccurate measurements. The transverse inertia effect may lead to the increase of the dynamic strength of the concrete to be measured, rather than its actual strain rate effect [25]. The friction between the specimen and the bars may lead to a complex tri-axial stress state, which exaggerates the true strength of tested materials [26]. Because the ultimate strain is very small (less than 1% generally), UHPC may fracture during the rise of the incident pulse [27]. Therefore, it is crucial to ensure stress equilibrium (SE) of the specimen during deformation. The following sections 2.2 and 2.3 present detailed improvement methods to the deficiencies of the SHPB system, especially considering UHPC.

2.2. Optimization of the aspect ratio of the specimen

Due to the Poisson’s ratio effect, inertia in SHPB tests influences the dynamic compressive properties of UHPC. An optimum aspect ratio is proposed to minimize the inertial effect: $L_s/D_s = \sqrt{\frac{3\mu}{2}}$ [28]. Where $\mu$ and $D_s$ refer to Poisson’s ratio and diameter of the specimen, respectively. The friction effect can be lessened by lubrication and choosing the specimen’s length to diameter ratio range from 0.5 to 1.0, as well as diminishing the area mismatch between the specimen and the bars ($D_s = 0.8D_b$) [29], where $D_b$ represents the diameter of input bar. For UHPC, various Poisson’s ratios have been reported, ranging from 0.16 to 0.21, corresponding to the length to diameter ratio of 0.35–0.40. As shown in Table 1 in the next section, in the summarized literature, aspect ratio ranges from 0.33 to 1, in which 0.5 is commonly adopted in the experiments. ASTM C192/C192M-16a [30], the standard for making specimens, suggests that the specimen diameter should be at least three times the maximum coarse aggregate size to eliminate the effects of heterogeneity. For UHPC with coarse aggregates, specimen diameter is

![Fig. 1. Typical strain rates and corresponding loading cases.](image-url)
recommended to be at least five times the maximum coarse aggregate size to eliminate the effects of heterogeneity and minimize data discretization of the SHPB test [31].

2.3. Pulse shaping technique

To ensure the validity of the SHPB test, pulse shapers are needed to achieve SE and constant strain rate to ensure the accuracy of experimental results [32,33]. The time for SE has been suggested as 5–10 times in Ref. [34], π times in Ref. [35], or at least 4 times of the transit time in Ref. [36]. The transit time can be counted by the length and the longitudinal wave speed of the specimen, namely \( t_0 = L_0/C_0 \) [23]. Ravichandran and Subhash [36] defined a parameter \( R(t) \) to evaluate the SE:

\[
R(t) = \frac{|\varepsilon(t) + \varepsilon(t_1) - \varepsilon(t_2)|}{|\varepsilon(t) + \varepsilon(t_1) + \varepsilon(t_2)|}
\]  

(1)

where \( \varepsilon(t_1), \varepsilon(t) \) and \( \varepsilon(t_2) \) represent incident pulse, reflected pulse and transmitted pulse respectively. A specimen is assumed to achieve stress equilibrium when \( R(t) \) is smaller than 5%.

Materials such as copper, brass, aluminum, and rubber have been used as pulse shapers to satisfy various experimental conditions [37–40]. As shown in Fig. 3, regular SHPB generates a similarly trapezoidal incident stress, while SHPB with a pulse shaper generates half-sine incident stress and prolongs the rising time of the pulse [41]. Because of the ultra-high strength of UHPC, the striker bar velocity is always faster. Increasing the striker bar velocity increases the strain rate and decreases the rising time [42]. Especially for UHPC containing large aggregates, a longer size of the specimen is used to satisfy the homogeneity, leading to a longer transit time. Hence, a longer rising time of the incident pulse is needed to achieve SE. The thickness of pulse shapers has effects on the rise time, i.e., an increase in thickness prolongs the rise time, as shown in Fig. 3. Therefore, for UHPC, thicker pulse shapers should be used in SHPB experiments. Additionally, to achieve constant strain-rate deformation in the specimen, the incident pulse generally needs to have an analogical shape to the stress response of the tested specimen, which is represented by the transmitted signal [43].

2.4. SHPB tests in different strain rates

In Table 1, the literature concerning the dynamic properties of UHPC using SHPB are summarized to provide an overview. The types of SHPB, strain rates, materials, specimen size, the aspect ratio of specimen, and studied properties are presented in Table 1. Proportions of different strain rates of UHPC reported in the summarized literature in Table 1 are evaluated, as shown in Fig. 4. For SHPB tests, three to five strain rates are usually used to analyze the dynamic performance of UHPC at different impact velocities. The strain rates of UHPC achieved by SHPB tests mainly range from 10 s\(^{-1}\) to 350 s\(^{-1}\), beyond which the specimens pulverize entirely. Samples usually begin to crack and fail in the strain rate range of 50–100 s\(^{-1}\). In the multiple impact test, the strain rate of the first time is usually low, ranging from 10 s\(^{-1}\) to 50 s\(^{-1}\) [45,46]. Then, the strain rate increases with the increase of the impact number. The factors, including steel fiber contents and types, steel fiber orientations, coarse aggregates, nanomaterials, temperature condition, and loading rate on the dynamic characteristics of UHPC are summarized, which show a great variety. The effects of these parameters will be systematically analyzed and discussed in Section 3.

3. Dynamic compressive properties of ultra-high performance concrete

3.1. Dynamic compressive strength

3.1.1. Effects of steel fiber

(1) Effects of steel fiber content

The fiber incorporation contributes the most to the dynamic properties of UHPC, among which steel fiber has the most distinct influence. The randomly displaced steel fibers work as bridges to resist the development of the cracks and limit the transverse deformation of the specimens, leading to the enhanced impact resistance [48]. Zhang et al. [45] reported that the dynamic strength was increased as well as the static strength with the addition of steel fibers, and UHPC showed a noticeable strain rate effect, the peak stress increased rapidly with the increase of strain rate. The analogous conclusions were drawn by Lai et al. [43], who ascribed the strain rate sensitivity to two causes: the time-dependent movement of free water passing through voids and pores and the time-dependent nature of crack growth relative to the loading rate. Similar to Refs. [48,72,73], Zhang et al. [53] concluded that dynamic compressive strength increased consistently with the increasing steel fiber volume. However, it must be noted that the workability of UHPC declined with the addition of steel fibers [74].

The values of peak strength from previous literature under dynamic loading are summarized in Fig. 5. In which “SF”, “LSF”, “SSF” and “HSF” represent steel fiber, long steel fiber, short steel fiber and hooked steel fiber, respectively. The steel fiber properties used in the literature are shown in Table 2. It is noteworthy that dynamic compressive strength of UHPC increases consistently with the increased strain rate and steel fiber content. Obviously, at a given strain rate, the data residing at the lower part of Fig. 5 overall come from UHPC without fiber reinforcement. At a relatively low strain rate, the peak strength of UHPC is smaller than the compressive strength under quasi-static conditions. For instance, in work [53], the peak strength of UHPC with 2% steel fibers at 19 s\(^{-1}\) is 90.2 MPa, and the quasi-static compressive strength is 151.2 MPa. At the strain rate 26 – 47 s\(^{-1}\), the peak strength ranges between 130 – 159.2 MPa. A similar conclusion can be found in Ref. [63]. The specimen does not fracture under the low-speed impact, which leads to this phenomenon. When the strain rate further increases, the peak strength exceeds the quasi-static compressive strength and shows strain rate effect

Fig. 2. Schematic design of SHPB system and the force diagram of the specimen.
leads to fiber-caking, material inhomogeneity, and void increase, the mechanical properties of UHPC [75–77]. The high steel fiber fraction leads to fiber-caking, material inhomogeneity, and void increase, resulting in decreased strength as the steel fibers further increase [78]. There exists an optimal dosage, beyond which the dynamic properties decrease with the increase of steel fiber. The length of steel fiber, the type of steel fiber and the mineral admixtures all influence the optimal dosage.

Table 1
The dynamic compression tests of UHPC studied by using SHPB system.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Material</th>
<th>Strain rate (s⁻¹)</th>
<th>Bar diameter (mm)</th>
<th>Specimen diameter (mm)</th>
<th>Specimen length (mm)</th>
<th>Aspect ratio</th>
<th>Studied properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>[47]</td>
<td>RPC with 2% steel fiber, 0.1% polypropylene fiber</td>
<td>70–250</td>
<td>40</td>
<td>30</td>
<td>10</td>
<td>0.33</td>
<td>(\varepsilon_d), DIF, dynamic stress-strain curves</td>
</tr>
<tr>
<td>[48]</td>
<td>RPC with 0%, 1.5%, 2% steel fiber</td>
<td>45–145</td>
<td>50</td>
<td>50</td>
<td>25</td>
<td>0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), DIF, failure modes</td>
</tr>
<tr>
<td>[49]</td>
<td>UHPC with 0%, 2%, 3%, 4% steel fiber</td>
<td>24.9–131.8</td>
<td>75</td>
<td>70</td>
<td>35</td>
<td>0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), (E_d), fracture pattern</td>
</tr>
<tr>
<td>[50]</td>
<td>UHPC with 0%, 3%, 4% steel fiber</td>
<td>23.7–99.2</td>
<td>75</td>
<td>70</td>
<td>35</td>
<td>0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), (E_d), fracture pattern</td>
</tr>
<tr>
<td>[51]</td>
<td>UHPC with 0%, 3%, 4% steel fiber</td>
<td>17.1–92.9</td>
<td>74</td>
<td>70</td>
<td>35</td>
<td>0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), dynamic stress-strain curves, failure modes</td>
</tr>
<tr>
<td>[52]</td>
<td>UHPC with 0%, 1%, 1.5%, 2%, 3% steel fiber</td>
<td>20–105</td>
<td>74</td>
<td>56</td>
<td>26</td>
<td>0.46</td>
<td>(\varepsilon_d), (\varepsilon_f), dynamic stress-strain curves, numerical simulation</td>
</tr>
<tr>
<td>[53]</td>
<td>UHPC with 0%, 1%, 2%, 3%, 4% steel fiber</td>
<td>10–114.7</td>
<td>75</td>
<td>75</td>
<td>35</td>
<td>0.47</td>
<td>(\varepsilon_d), (\varepsilon_f), energy absorption model, failure modes</td>
</tr>
<tr>
<td>[54]</td>
<td>UHPC with 0%, 1%, 2%, 3%, 4% steel fiber</td>
<td>12–115</td>
<td>75</td>
<td>72</td>
<td>35</td>
<td>0.49</td>
<td>(\varepsilon_d), (\varepsilon_f), fracture patterns, microstructural features</td>
</tr>
<tr>
<td>[55]</td>
<td>UHPC with 0%, 3%, 4% steel fiber</td>
<td>80.7–267.4</td>
<td>75</td>
<td>50</td>
<td>50</td>
<td>1</td>
<td>(\varepsilon_d), (\varepsilon_f), DIF model</td>
</tr>
<tr>
<td>[56]</td>
<td>UHPC with 2.5%MF06, 2.5%MF15, 2.5%TF03, 2.5%TF05</td>
<td>60–200</td>
<td>75</td>
<td>75</td>
<td>37</td>
<td>0.49</td>
<td>(\varepsilon_d), DIF, failure patterns</td>
</tr>
<tr>
<td>[57]</td>
<td>UHPC with 3% nano-CaCO₃, 3%nano-SiO₂, 3% nano-Al₂O₃, 3% nano-TiO₂</td>
<td>40–94</td>
<td>75</td>
<td>75</td>
<td>37.5</td>
<td>0.5</td>
<td>(\varepsilon_d), DIF, failure patterns</td>
</tr>
<tr>
<td>[58]</td>
<td>UHPC with 3% nano-CaCO₃, 3%nano-SiO₂, 3% nano-Al₂O₃, 3% nano-TiO₂, 5% nano-CaCO₃, 1% nano-CaCO₃</td>
<td>60–80</td>
<td>75</td>
<td>75</td>
<td>37.5</td>
<td>0.5</td>
<td>(\varepsilon_d), DIF model, failure patterns</td>
</tr>
<tr>
<td>[59]</td>
<td>UHPC with 2% long fiber, 1.5% long fiber and 0.5% short fiber, 1.0% long fiber and 1.0 short fiber, 0.5% long fiber and 0.5 short fiber, 2% short fiber</td>
<td>100–204.8</td>
<td>100</td>
<td>92</td>
<td>46</td>
<td>0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), fracture energy, crack control mechanism</td>
</tr>
<tr>
<td>[60]</td>
<td>UHPC</td>
<td>30–200</td>
<td>25.4</td>
<td>23.8</td>
<td>9.2</td>
<td>0.39</td>
<td>DIF models with different dimensions of Al and Cu pulse shapers</td>
</tr>
<tr>
<td>[61]</td>
<td>UHPC with 0%, 0.5%, 1%, 2%, 4% steel fiber, 0.5% basalt fiber, 0.5% polyvinyl alcohol fiber</td>
<td>22–110</td>
<td>25.4</td>
<td>23.8</td>
<td>9.2</td>
<td>0.39</td>
<td>(\varepsilon_d), DIF model, numerical simulation</td>
</tr>
<tr>
<td>[62]</td>
<td>UHPC with 4% steel fiber</td>
<td>130–200</td>
<td>76</td>
<td>76</td>
<td>76</td>
<td>1</td>
<td>(\varepsilon_d), dynamic failure progress under high speed video</td>
</tr>
<tr>
<td>[63]</td>
<td>UHPC with 0%, 1%, 2% micro-straight steel fiber, 1%, 2% hooked steel fiber</td>
<td>17.6–328.4</td>
<td>50</td>
<td>48</td>
<td>35</td>
<td>0.73</td>
<td>dynamic stress-strain curves, DIF, failure patterns, (W_u), visco-elastic damage model</td>
</tr>
<tr>
<td>[64]</td>
<td>RPC with 0%, 2%, 5% steel fiber</td>
<td>75–274</td>
<td>40</td>
<td>36</td>
<td>17.5</td>
<td>0.49</td>
<td>(\varepsilon_d), (\varepsilon_f), dynamic stress-strain curves, dynamic damage-softening model</td>
</tr>
<tr>
<td>[65]</td>
<td>RPC with 0%, 2%, 5% steel fiber and 0.2% polypropylene fiber</td>
<td>72–317</td>
<td>40</td>
<td>36</td>
<td>17.5</td>
<td>0.49</td>
<td>(\varepsilon_d), (\varepsilon_f), DIF, (W_u), damage variable</td>
</tr>
<tr>
<td>[66]</td>
<td>RPC with 0%, 1%, 1.5% super-fine stainless wire</td>
<td>94–926</td>
<td>37</td>
<td>30</td>
<td>15</td>
<td>0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), DIF, (W_u), strain-stress curve, dynamic constitutive model</td>
</tr>
<tr>
<td>[67]</td>
<td>RPC with 0.2% polypropylene fiber</td>
<td>107–356</td>
<td>40/100</td>
<td>36/75</td>
<td>17.5/37.5</td>
<td>0.49/0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), (W_u), of different specimen size</td>
</tr>
<tr>
<td>[68]</td>
<td>UHPC with 2.5% steel fiber</td>
<td>35.4–123.6</td>
<td>100</td>
<td>70</td>
<td>35</td>
<td>0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), (E_d), (W_u)</td>
</tr>
<tr>
<td>[69]</td>
<td>UHPC with 1% steel fiber and 2%polypropylene fiber</td>
<td>98.1–347</td>
<td>75</td>
<td>50</td>
<td>25</td>
<td>0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), DIF, (E_d), fracture pattern</td>
</tr>
<tr>
<td>[70]</td>
<td>UHPC with 1% steel fiber and 2%polypropylene fiber</td>
<td>76–362</td>
<td>75</td>
<td>50</td>
<td>25</td>
<td>0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), DIF, strain-stress curve</td>
</tr>
<tr>
<td>[71]</td>
<td>UHPC with 2% steel fiber</td>
<td>117.7–229.2</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), DIF, HJC model, numerical simulation</td>
</tr>
<tr>
<td>[72]</td>
<td>UHPC with 3% steel fiber</td>
<td>30.7–167.9</td>
<td>50</td>
<td>50</td>
<td>25</td>
<td>0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), DIF, strain-stress curve, failure patterns</td>
</tr>
<tr>
<td>[73]</td>
<td>UHPC with 2% steel fiber (perpendicular, random, and parallel)</td>
<td>155–291</td>
<td>80</td>
<td>60</td>
<td>30</td>
<td>0.5</td>
<td>(\varepsilon_d), (\varepsilon_f), DIF, strain-stress curve, failure pattern, dynamic constitutive model</td>
</tr>
</tbody>
</table>
Based on experimental data in the existing literature [43–48, 53–55], a prediction model is proposed in the present study by considering two factors: strain rate and fiber volume fraction. The model, non-dimension based, is expressed as:

\[
f_d = f_{d_{\text{max}}} \left[ 0.36 + 1.31 \frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_{d_{\text{max}}}} - 2.79V_f - 0.81 \left( \frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_{d_{\text{max}}}} \right)^2 + 77.01V_f^2 + 2.67 \frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_{d_{\text{max}}}} \right]
\]

\[0 \leq V_f \leq 5\% , \ 8.59 < \dot{\varepsilon}_d < 145\]

\[R^2 = 0.9 \] (2)

where \(f_d\) is dynamic compressive strength and \(f_{d_{\text{max}}} = 212.7\) MPa \(\dot{\varepsilon}_d\) is the strain rate in SHPB test and \(\dot{\varepsilon}_{d_{\text{max}}} = 145\) s\(^{-1}\). \(V_f\) represents the fiber volume fraction.

The comparison between the modeling results and experimental data in the literature is presented in Fig. 6. In the summarized literature, the

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Shape</th>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>Aspect ratio</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[37]</td>
<td>Short straight</td>
<td>13</td>
<td>0.175</td>
<td>74</td>
<td>1800</td>
</tr>
<tr>
<td>[23]</td>
<td>Short straight</td>
<td>13</td>
<td>0.2</td>
<td>65</td>
<td>2800</td>
</tr>
<tr>
<td>[23]</td>
<td>Hooked</td>
<td>25</td>
<td>0.5</td>
<td>50</td>
<td>1200</td>
</tr>
<tr>
<td>[40]</td>
<td>Short straight</td>
<td>13</td>
<td>0.22</td>
<td>59</td>
<td>–</td>
</tr>
<tr>
<td>[45]</td>
<td>Short straight</td>
<td>13</td>
<td>0.2</td>
<td>65</td>
<td>2800</td>
</tr>
<tr>
<td>[45]</td>
<td>Short straight</td>
<td>6</td>
<td>0.2</td>
<td>30</td>
<td>2800</td>
</tr>
<tr>
<td>[41]</td>
<td>Short straight</td>
<td>13</td>
<td>0.16</td>
<td>81</td>
<td>2800</td>
</tr>
<tr>
<td>[18]</td>
<td>Short straight</td>
<td>13</td>
<td>0.2</td>
<td>65</td>
<td>2800</td>
</tr>
<tr>
<td>[38]</td>
<td>Short straight</td>
<td>13</td>
<td>0.175</td>
<td>74</td>
<td>2500</td>
</tr>
<tr>
<td>[39]</td>
<td>Short straight</td>
<td>13</td>
<td>0.175</td>
<td>74</td>
<td>2800</td>
</tr>
<tr>
<td>[49]</td>
<td>Short straight</td>
<td>10</td>
<td>0.12</td>
<td>83</td>
<td>&gt;2500</td>
</tr>
<tr>
<td>[51]</td>
<td>Short straight</td>
<td>12</td>
<td>0.16</td>
<td>75</td>
<td>≥2000</td>
</tr>
</tbody>
</table>

Fig. 3. Incident pulses with various pulse shapers [44].

Fig. 4. Proportions of different strain rates of UHPC reported in literature of Table 1.

Fig. 5. Peak strength of UHPC with different volume fractions fiber.

Table 2
Steel fiber properties used in literature.
The dynamic strength of UHPC with the same volume of steel fibers varies significantly under a similar strain rate. The increases of dynamic strength of UHPC with the same increase volume of steel fibers also differ significantly. The different geometric characters, mechanical characters of steel fiber and mixture proportions of UHPC contribute to this phenomenon. The different testing devices (e.g., different diameter, different pulse shaper), specimen geometry and size effect can cause various errors in measurements, which can also lead to the discrete dynamic strength under a similar strain rate. In the acquired model in this study, the value of root mean squared error (RMSE) is 13.4 MPa, which represents the degree to which the fitted value deviates from the experimental data. The average value of dynamic strength is 157.75 MPa and the RMSE divided by the mean dynamic strength is approximately 8.5%, indicating that the prediction model proposed can predict the dynamic strength well despite the data dispersion caused by the above reason.

(2) Effects of steel fiber types, steel fiber aspect ratio and hybrid steel fiber

The commonly used steel fibers are shown in Fig. 7. To identify the influences of different fiber types including micro-straight and twisted steel fiber as well as fiber aspect ratio on the dynamic properties of UHPC, SHPB tests were carried out in Ref. [56]. In this study, the UHPC with micro-straight fiber showed higher dynamic strength, and the increase of fiber content, steel fiber length and aspect ratio benefited the dynamic strength. Ren et al. [38] compared the micro-straight and hooked steel fiber, and revealed that micro-straight steel fiber provided better reinforcement on dynamic compressive strength.

The hybrid fiber has been widely used in normal strength concrete (NSC) and high strength concrete (HSC), as better mechanical performance can be obtained by taking the advantage of different reinforcing fibers. Hybrid fibers mainly include the following types: hybrid combination of different diameter steel fibers, hybrid combination of different shapes steel fibers and hybrid combination of steel fibers and other kinds of fibers. The hybrid fibers used in UHPC are mainly different kinds of steel fibers. Wu et al. [59] utilized different length of steel fiber (6 mm and 13 mm) to investigate the effects of hybrid fibers. It was concluded that the hybrid steel fiber (1.5% long and 0.5% short steel fiber) had the best mechanical characteristics, concerning both static and dynamic performance. Hou et al. [64] mixed two different kinds of fibers (PP fiber and steel fiber) into UHPC to investigate the effect of hybrid fiber. The results indicated that adding PP fiber can reduce the peak strength of RPC and the low elasticity modulus of PP fiber is accounted for this phenomenon, which obstructs its application in UHPC. Nevertheless, PP fiber had good ductility, good chemical stability. The addition of PP fiber can noticeably improve the crack-resistance behavior and ductility of UHPC. Moreover, the melting of PP fibers at high temperature (i.e. over 165 °C) will create extra channels that will help with the release of the pressure created by the water vapor, which contributes to enhanced fire resistance of UHPC.

(3) Effects of steel fiber orientation

In addition to the content and type of steel fiber, fiber orientation also exerts an essential role in the mechanical properties of UHPC [79–82]. Groeneveld et al. [62] investigated the influence of fiber alignment on dynamic strength of UHPC. Based on the orientation effect in compression, the orientation ratio could be expressed as follows:

\[ \eta_i = \frac{1}{N} \sum_{j=1}^{N} \cos(\theta) \]

where \( N \) refers to the total number of fibers, and \( \theta \) is the angle that the ith fiber makes with the axis of loading. \( \eta_i \) refers to the fraction of fiber length that is projected parallel to the applied load. When the fiber direction is in line with the loading direction, \( \eta_i \) is 1.0. When fiber direction is perpendicular to loading direction, \( \eta_i \) is zero. The specimens show a realistic level of flow-induced preferential fiber orientation, but fibers are not perfectly aligned, which makes it challenging to investigate the effects of fiber orientation reliably. Nevertheless, the results indicated that dynamic compressive strength was independent of the perpendicular number of steel fibers [62]. Huang et al. [71] utilized flow-induced casting method to control fiber orientations and investigated the effect of fiber orientation on dynamic properties enhancement of UHPC. However, the results showed that specimens with steel fiber orientation mainly perpendicular to the loading direction exhibited the highest dynamic performance. This phenomenon was attributed to the fact that fibers perpendicular to compressive stress were the most efficient at bridging cracks and improving strength [83].

3.1.2. Effects of aggregate size

Recently, coarse aggregates are introduced into UHPC to reduce the production cost and enhance the volume stability, which helps expand its engineering application [84–86]. The SHPB system was employed to evaluate the dynamic compressive strength of UHPC with a maximum coarse aggregate size of 10 mm in Ref. [50]. Compared with the cases without coarse aggregates, the composite material’s resistance to high velocity impact did not show an obvious decreasing trend, instead showed closed to or even improved performance. Three kinds of coarse aggregate with the maximum size of 10 mm, 15 mm and 20 mm were
utilized to make high performance cementitious composite (HPCC) in Ref. [87]. The experiments indicated that the addition of coarse aggregate was helpful for impact resistance, which can be attributed to the higher strength of the coarse aggregates.

Li et al. [85] investigated the effect of coarse basalt aggregates with the maximum size of 16 mm on the properties of UHPC and found that the coarse basalt aggregate resulted in a limited decline in mechanical strength. This research demonstrated that it was possible to use a large size of coarse aggregate in UHPC on a large scale. However, compared to the research of quasi-static compression, the research of dynamic compression of UHPC with a large size of coarse aggregate is yet very limited. Therefore, the maximum size of the coarse aggregate, the volume fraction of the coarse aggregate, the damage of coarse aggregates during loading, and the influence of the interaction between the coarse aggregate and the steel fiber on the dynamic characteristics of UHPC should be studied in the future study.

3.1.3. Effects of nanomaterials

In recent years, the development of nanotechnology has attracted great attention [88–92]. Due to the super fine size, nanoparticles can fill the voids of the cement matrix and involve in the cement hydration, consequently improving the performance of concrete significantly [93–95]. The effects of different types and content of nanoparticles on the dynamic properties of UHPC were investigated in Ref. [58]. The results revealed that when the content of nanomaterials increased from 1% to 3%, the dynamic compressive strength increased significantly, when it further increased from 3% to 5%, the dynamic compressive strength decreased. Moreover, the researchers found that the effect of different types of nanomaterials on the dynamic strength of UHPC was not obvious. A similar conclusion was drawn in Ref. [57]. It can be seen from the existing literature that efforts are still primarily spent on making use of nanomaterials to refine the microstructure of UHPC. Nevertheless, how different nanomaterials refine the microstructure and how can the refinement be linked with dynamic properties have not been studied yet. The dynamic enhancement can be explained from the Stefan effect [9], which is strongly correlated with the microstructure of UHPC. Therefore, in the future, investigations should be carried out to deepen this understanding.

3.1.4. Effects of temperature

Temperature is an important factor affecting the mechanical behavior of concrete. In Ref. [96], the dynamic compressive strength decreased by 20% at 200°C. The free water evaporated increased porosity, and water in concrete softened the cement gel and attenuated the surface forces between gel particles, all leading to the decrease of dynamic strength. With the increase of temperature, the vapor within the concrete produced steam pressure, resulting in the further deterioration in strength. The dynamic compressive strength increased at 400°C by nearly 14% compared to the room temperature. The high-temperature and high-pressure curing environment led to this improvement [67]. The increase in deformation difference between aggregate and concrete paste and the decomposition of Ca(OH)2 resulted in the strength loss from 400°C to 600°C. The dynamic strength at 600°C decreased by 16% on average. CaCO3 started to decompose and the aggregate became loose from 600°C to 800°C. The largely developed interface cracks and the loss of binder force led to a sharp decrease in strength.

Kim et al. [97–99] investigated the effect of cryogenic temperature on the flexural behaviors and tensile response of UHPC under very low strain rates. However, the dynamic characteristics of concrete under low temperature are less studied. Qiao et al. [100] examined the effect of temperature, strain rate, water to cement (w/c) ratio and maximum aggregate size on dynamic behavior of concrete. The sensitivity of dynamic compressive strength to strain rate increased as temperature decreased. The study indicated that the influence sequence of factors was: temperature > strain rate > w/c ratio > maximum aggregate size.

Large quantities of concrete structures are built in cold regions, but the study of dynamic behavior of concrete under low temperatures is rare. Thus, more experimental research needs to be done on the dynamic properties of concrete under low temperature, especially for UHPC. The following critical factors such as degree of capillary saturation, pore size distribution, and effects of freeze-thaw conditions that influence the dynamic characteristics of UHPC should be considered in future research.

3.1.5. Effects of specimen size

Some studies have reported that specimen size significantly affects the static and dynamic properties of concrete materials [66,101–105]. Studies concerning dynamic properties of UHPC are typically evaluated on specimens of varying sizes ranging from 9.2 to 50 mm in height and 23.8–100 mm in diameter, as shown in Table 1. Hao et al. [104] found that the dynamic strength increased with the specimen diameter at the same strain rate by comparing three different diameters with the same aspect ratio. This phenomenon was attributed to the lateral inertia confinement and end friction confinement effect dependent on specimen size. A similar conclusion was found by Cao et al. [66], who utilized SHPB with different diameter (40 mm and 100 mm) to investigate the size effect on UHPC dynamic properties. Hao et al. [104] reported that the dynamic stress decreased with the increasing aspect ratio of the same diameter specimens. However, Li et al. [105] found that the effect of aspect ratio on dynamic strength is insignificant owing to the significantly reduced coefficient of friction in impact tests. It can be concluded that the dynamic strength increases with the specimen diameter with the same aspect ratio. Nevertheless, existing studies are insufficient to determine specimen size effect with the same diameter but different aspect ratios. Additionally, a quantitative analysis conclusion of the size effect on UHPC dynamic properties still cannot be drawn.

3.2. Peak strain

3.2.1. Effect of strain rates

Peak strain can be utilized to describe the deformation property, at which dynamic stress reaches the highest [106]. The peak strain of UHPC from the existing literature under dynamic loading are summarized in Fig. 8. The values of peak strain do not show a consistent trend as the fiber increases and the strain rate increases. Jiao et al. [55] believed that the peak strain increased with the increase of the strain rate. Their conclusions are in well agreement with the results in Refs. [43,51,59,63,64,106–110]. Li et al. [111] attributed the strain rate effect of peak strain to progress of cracks in the concrete. As the increase of the strain rate, the failure caused by several macroscopic cracks transformed into the failure caused by multiple microscopic cracks, which enhances the cumulative strain. Additionally, the pore size and distribution are also important factors affecting the peak strain changing with strain rate. However, Harsh et al. [112], Harris et al. [113] and Wang et al. [43] concluded that the peak strain remained almost constant as the strain rate changed.

3.2.2. Effect of steel fibers

Jiao et al. [55] observed that as the steel fiber contents increased, the peak strain increased. This was consistent with the conclusions in Ref. [43]. However, the values of peak strain showed no clear trend as the increase of steel fibers in Refs. [38,54]. Wu et al. [59] concluded that the volume of hybrid steel fibers seemed not to show an obvious effect on the peak strain. Ren et al. [38] also found that the peak strain remained almost invariable with the change of steel fiber type and content under the different strain rate.

There are controversial conclusions on the tendencies of peak strain for UHPC with the increasing strain rate and steel fiber. In overall, we can conclude that the fibers content plays a trivial role in the strain rate. Although peak strain increases as a function of strain rate in a specific mix design, the overall trend of the reviewed papers is rather vague. For
instance, for concretes with similar static strength without fiber reinforcement \cite{59,66}, observed very different peak strain of 0.006 and 0.003 under similar strain rate of about 130 s$^{-1}$. This might be explained by the adopted large content of slag in the former study, which has a latent reactivity, therefore affecting the microstructure development at the testing ages, i.e. 28 days that results in lower elastic modulus development. Further aspects, including for instance, different geometric characters and mechanical properties of steel fiber can vary the bonding quality with the UHPC matrix, mixture proportions strongly affect the mechanical properties of UHPC as well.

3.3. Stress-strain relationship

Stress-strain curve is an important index used to evaluate the dynamic characteristics. Hou et al. \cite{64} employed a SHPB apparatus to investigate the stress-strain curve of RPC with different fiber contents. A classical dynamic stress-strain relationship for different contents of steel fibers changing with strain rates is shown in Fig. 9.

As shown in Fig. 9, the shapes of stress-strain curve of RPC specimens are similar. The different steel fiber content and stain rates only affect the proportions and values of different stages. It can be seen from Fig. 9 (b) that the characteristics of the stress-strain curve can be classified into three stages \cite{64}: elastic stage (O-A); elastic-plastic deformation stage (A-B); descending stage (B-C). Elastic stage and elastic-plastic deformation stage are rising stages, in which the strain increases with the increase of stress. In the rising stage, the stress-strain curve is initially linear, then, develops to the strain-hardening stage, in which the steel fibers begin to exert the bridging actions and a large amount of energy is dissipated as the steel fibers pull out. At the same time, internal cracks start to progress as the strain further increases. After the stress reaches the peak, the specimen goes into the damage-softening stage, with continuous inner crack propagation and expansion, the visible cracks increase \cite{38}.

3.4. Dynamic elastic modulus

The elastic modulus is a parameter describing the deformation capacity of materials. Elastic modulus of UHPC under dynamic loading from existing literature are plotted in Fig. 10. In which “PPF” represents polypropylene fiber. Jiao et al. \cite{55}, Lai et al. \cite{43} and Hou et al. \cite{63} found that the value of elastic modulus obviously increased with the increase of strain rate and the volume fraction of the steel fibers had no effect on elastic modulus. Similar results were reported by Sukontasukkul \cite{114} and Shkolnik \cite{115}. Ren et al. \cite{38} reported that the elastic modulus increased slightly with the increase of strain rate. As shown in Fig. 10, the increasing rate of elastic modulus in Fig. 10 (a) is larger than
that in Fig. 10(b), which can be attributed to different mix compositions, different water to cement (w/c) ratio and different specimen size. However, the exact mechanism is not clearly understood. For instance, under a similar strain rate, [63] reported a much higher dynamic modulus than [116], which is caused by the obviously smaller peak strain observed in Ref. [63]. However, from the existing information, we cannot derive why the tested concrete is much more ductile in the later work. The effect of steel fiber contents and types (micro-straight and hooked) on the elastic modulus was also investigated in Ref. [24]. It was concluded that the steel fiber contents and types had very limited effect work. The effect of steel fiber contents and types (micro-straight and rising strain rate, the relation between the elastic modulus and strain can not derive why the tested concrete is much more ductile in the later temperature from 200 ◦C to 800 ◦C, as illustrated in Fig. 10(c). It is noticed that the values of elastic modulus in Ref. [67] are obviously smaller than that in Figs. 9(a) and Fig. 10(b), although the tested UHPC has a relatively high static compressive strength of 162.8 MPa at room temperature. The reason may lie in the applied PP fiber. Further, it can be clearly observed that the softening of UHPC due to cracks and vapor pressure led to the decrease in elastic modulus. Moreover, changes in the chemical composition of UHPC, such as the decomposition of C-S-H gels, also resulted in the decline of elastic modulus. This is consistent with the findings of Su et al. [96].

4. Models for dynamic increase factor (DIF) and energy absorption

4.1. Dynamic increase factor (DIF)

The DIF is defined as the ratio of the dynamic strength to the quasi-static strength, which has been used to characterize the variation of strength caused by loading rate [38]. The mechanism about the effect of strain rate on DIF has not been fully understood. Viscoelastic character of the hardened cement paste and time-dependent micro-crack growth may account for the macroscopic sensitivity to strain rate [25]. Under quasi-static loading, there exists enough time for micro-cracks to develop into macro-cracks [48,59,117]. However, the loading time is much shorter under impact loading. Before micro-cracks propagate into macro-cracks, more new micro-cracks have been nucleated and enlarged, consuming more energy and leading to higher compressive strength. Li and Meng [25] observed that the lateral confinement in the SHPB test was an important factor causing the dynamic strength enhancement of concrete. Mindess et al. [118] stated that the time-dependent movement of free water through pores in the matrix resulted in the strain rate sensitivity of concrete.

4.1.1. Effect of steel fiber

The values of DIF from the literature are summarized in Fig. 11. It can be seen that the values of DIF are proportional to the strain rate and inversely proportional to steel fiber content. The DIF values of plain UHPC are higher than that of UHPC with various steel fiber content and type, which indicates that UHPC with steel fiber is less sensitive to high strain rate [46]. The similar conclusion is found in Refs. [47,61]. Zhang et al. [45] reported that DIF improved with the increase of strain rate and reduced with the rise of steel fibers. Ben et al. [38] investigated the influence of two typical steel fibers and content on DIF. It was concluded that the values of DIF declined with the increase of steel fiber content for both fiber types, and the DIFs of UHPC with hooked steel fiber were relatively higher than those with micro-straight steel fiber with the same fiber dosage. The reason may lie in that a higher content of steel fibers could enhance the quality of UHPC and the micro-straight steel fiber had comparatively better performance, which resulted in the lower DIFs. Similar to the conclusions in Ref. [38], Bischoff and Perry [110] reported that a poorer quality concrete exhibited a higher value of DIF.

Wu et al. [59] examined the effect of hybrid steel fibers on DIF and found that specimens with 2% SSF had higher DIFs than the specimens with 2% LSF. The DIFs of specimens with hybrid steel fibers (i.e., 1.5% LSF and 0.5% SSF, 1.0% LSF and 0.5% SSF and 0.5% LSF and 1.5% SSF) in overall show further enhanced trend compared to sole fiber type and the combination of 1.0% LSF and 1.0% SSF shows the best DIF enhancement effect. Liang et al. [67] reported that DIFs had the highest values at room temperature. The DIFs showed the smallest under the 200 ◦C testing conditions, which can be explained by the severely produced internal vapor pressure caused by the free water evaporation. The DIFs then further increased with the increase of temperature up to 600 ◦C but then showed a reduction attributed to the samples’ drastic mechanical and integrity degradation under higher temperatures. Moreover, it is clearly seen from Fig. 10 that at high strain rate, the DIFs of the testing samples under the high temperatures are lower than the results from other literature, confirming again the synergistic effect of fire and impact loading on mechanical and volumetric stability of UHPC.

4.1.2. Models for dynamic increase factor (DIF)

Different models of DIF for compression have been proposed to count the strain rate effect, as summarized in Table 3. The DIF models proposed can be divided into two categories: empirical and curve-fitting method. The above formulae [25,38,119–122] and experimental data [38,54] are plotted in Fig. 12. The comparisons show that the formulæ proposed by the fib Model Code 2010 can be applied to NSC and HSC to describe the evolution of the DIF with relatively good accuracy. However, it generally overestimates the DIFs of UHPC. The transition strain rate in formula recommended by CEB model code and the fib Model Code 2010 is 30 s−1, which is applicable for NSC. The NSC is more sensitive to strain rate than UHPC, as a result, the transition strain rate of UHPC is larger than NSC. The transition strain rate of UHPC becomes higher as the increase of the steel fibers. In literature [38], $\varepsilon_c$ of UHPC with micro-straight steel fibers increases as the increase of steel fiber content. The value of $\varepsilon_c$ of UHPC with 2% with micro-straight steel fibers is higher than hooked ones. It can be concluded that the value of $\varepsilon_c$ is greater when UHPCs have a better impact performance. The conclusions agree with the results in Ref. [64].

The effect of lateral inertia confinement on DIF has been investigated by many researchers. However, the results of these studies are inconclusive and often contradictory. Cotsovos and Pavlovic [127] performed
numerical simulations of impact tests and found that lateral inertia confinement was the main factor causing DIF. On the other hand, Zhou and Hao [122] considered that the inertial confinement and strain rate effect were the two sources that contributed to the DIF. Their study showed that the inertial confinement could be ignored when strain rate was less than 200 s⁻¹ and strain rate effect was the main reason for DIF. Bragov et al. [128] found that the effect of inertial confinement was minimal at strain rates up to 10³ s⁻¹. Al-Salloum et al. [129] argued that different testing devices, specimen geometry, size effect and different material components (e.g., concrete grade, aggregate size, curing conditions, etc.) may lead to the difference in the DIF models. An effective model describing the DIF precisely is still missing. Further investigations are needed to develop a unified model through detailed studies considering the effect of these factors.

Most of the existing curve-fitting formulae for DIF are chiefly based on the power law variation and follow the logarithmic functions, in which the lateral inertia is not eliminated. It is necessary to quantitatively distinguish the lateral inertial effect and the real strain rate effect on DIF [130]. To precisely evaluate the relationship between DIF and strain rate, the lateral inertia confinement should be eliminated to obtain real material rate effect of UHPC. Thus, more precise test data that eliminate the effect of inertial confinement need to be obtained to propose predictive model. Nevertheless, it is difficult to eliminate the lateral inertia in SHPB test, and the numerical simulation would be a
4.2. Energy absorption characteristics

The energy absorption capacity is a significant dynamic property that is determined by the strength and the deformation degree [131, 132]. Toughness and specific energy absorption are the main parameters to evaluate the energy absorption capacity [133].

4.2.1. Toughness and specific energy absorption

Toughness is an important index to describe the energy absorption capacity, which can be calculated by Ref. [134]:

\[ W = \int_{0}^{\varepsilon} \sigma(t) \varepsilon(t) \, dt \]  
(4)

where \( \sigma \) and \( \varepsilon \) are the stress and strain, respectively.

Specific energy absorption (SEA) is described as the amount of stress wave energy per unit volume of the concrete absorbs [135]. In SHPB test, \( W_i, W_w, W_r \) represent the energy caused by incident, reflected and transmitted wave, respectively. \( W_i \), the energy that is absorbed by the specimen, can be described as [136,137]:

\[ W_i = W_e - W_w - W_r \]  
(5a)

\[ \text{SEA} = \frac{A_i C_0}{A_t l_t} \int [\varepsilon_i^2(t) - \varepsilon_r^2(t) - \varepsilon_l^2(t)] \, dt \]  
(5b)

where \( E_0, C_0 \) and \( A_0 \) represent the Young’s modulus, wave velocity in the bars and cross-sectional area of the SHPB bars, respectively. \( A_t \) and \( l_t \) refer to the cross-sectional area and the length of the specimen.

4.2.2. Analysis of energy absorption progress

The energy conversion goes along with the whole impact process of the SHPB test. In the elastic stage, the energy of the incident bar transforms into elastic energy and is stored in the specimen [122]. During the elastic-plastic stage, internal cracks start to progress and consume energy. Due to the bridging actions of steel fibers, the strain hardening stage occurs in which a large number of steel fibers begin to be pulled out. In the descending stage, a large number of steel fibers are pulled out, concrete matrixes are fractured and stress starts to unload. The energy absorption of the specimen consists of two parts: the energy consumed by the fracture of the concrete matrix and the energy consumed by the steel fibers pullout. In the elastic stage, the energy absorbed by the specimen tends to remain unchanged regardless of steel fiber content. The strain hardening stage and the descending stage can be defined as the high energy absorbing stage, during which the steel fiber pullout dissipates a large amount of energy. As shown in Fig. 9, the energy absorption increases with the increase of steel fiber content during the descending stage. As an important stage of energy absorption, the high energy absorbing stage can be regulated by fiber type and content. It is worth noting that the efficiency of fiber in absorbing energy is related to its bonding mechanism in UHPC matrix. The better the bonding force with the UHPC matrix, the higher energy is absorbed during the high energy absorbing stage. Alhozaimy et al. [138] found that replacing parts of cement with supplementary cementitious materials (SCMs) resulted in enhanced impact resistance because pozzolanic reaction improved the bond performance of PP fibers in the matrix. Wei et al. [70] reported that silane coupling agent (SCA) modified steel fiber can improve energy absorption of UHPC. The steel fiber-matrix interfacial bond is promoted by SCA, leading to absorbing more energy and postponing interfacial debonding.

The values of energy absorption of UHPC under high strain rates from the existing literature are presented in Fig. 13. It can be seen that the dynamic toughness increases almost linearly with the increased strain rate and higher strength and strain under a higher strain rate lead to an increase in the toughness of the UHPC. Hou et al. [63] concluded that the energy absorption ability of SFRPC was higher than PRPC, and the energy absorption of RPC increased with the increased strain rate and steel fiber. These trends agree well with the findings of Lai et al. [43], Zhang et al. [45] and Jiao et al. [55], who considered that a great amount of energy was consumed during the debonding and pullout of steel fibers from the matrix. However, Tai [139] found that the specimen with steel fibers absorbed less energy than that without steel fibers at low-speed impact. The researcher attributed this to the fact that the specimens were not fractured under a low-speed impact, and the reflection and transmission of energy were high, thus reducing the absorption of energy. Ren et al. [38] investigated the effects of steel fiber contents and types on the toughness of UHPC. The dynamic toughness of UHPC increased with the increasing steel fibers, regardless of the micro-straight and hooked steel fibers. In addition, UHPC with micro-straight steel fibers had a more prominent influence. Hou et al. [64] reported that the energy absorption ability of RPC was obviously higher than that of NSC and HSC. In the study, they also confirmed that the energy absorption of RPC increased with the increased strain rate while it had slight decline with addition of PP fiber.

4.2.3. Models for energy absorption

Based on experimental results in the literature [43,45,55,63], a prediction model of toughness is established by considering strain rate and steel fiber volume:

\[ W = -0.058 + 0.024 \varepsilon_d - 6V_f - 1.52\varepsilon_d \varepsilon_f^2 - 79.76V_f^2 + 0.34V_f V_i \]

\[ 0 \leq V_i \leq 5\%, \quad 8.59 < \varepsilon < 274 \]

\[ R^2 = 0.91 \]  
(6)

The comparison between the fitting model and experimental results in literature is illustrated in Fig. 14. It can be concluded that the model agrees well with the experimental data. Nevertheless, it should be noted that the fitting polynomial relation can only be used in the experimental range of loading rates and further validation of this model for other application conditions is still needed.
5. Dynamic constitutive models

5.1. ZWT model

5.1.1. ZWT model and modifications

A typical visco-elastic theory model (ZWT model) was proposed by Zhu, Wang and Tang, which consists of a nonlinear elastic spring, a low frequency Maxwell element and a high frequency Maxwell element [140]. Damage is an essential factor of concrete, so it is necessary to consider the damage factor (denoted as $D$). The ZWT model and the modified models considering damage factor are summarized, as shown in Table 4.

5.1.2. Comparison and analysis of models

The ZWT model is initially used to express the nonlinear viscoelastic constitutive characteristic of polymer materials, which does not consider the damage of materials. However, concrete materials have numerous pores and microcracks inside. To make the constitutive model more representative, damage factor $D$ is introduced to modify the ZWT model. Lai et al. [43] utilized ultrasonic wave velocity to quantify the damage degree of concrete material. In their study, the damage factor $D_1$ can be expressed by strain rate by linear regression. This is an effective way to consider the effects of damage without introducing more parameters. Considering the principle of strain-equivalence in damage mechanics, the damage evolution coefficients $\beta$ and $\alpha$ and the bearing capacity of the steel fibers $k$ are included to describe the damage factor $D_2$ in Ref. [141]. The method for obtaining the values of these parameters by experiment is not given, although they have clear physical implications. The values of the introduced parameters are acquired through the linear fitting method, which however results in difficulties in engineering applications. According to the continuum damage theory, the strength distribution is presumed to follow the Weibull function [142–145]. Wang et al. [73] proposed to characterize the cumulative probability of the failure. The parameters $m$ and $F_0$ are used to evaluate the damage evolution. $F_0$ and $m$ can be expressed by $V_f$ and $\dot{\varepsilon}$, therefore, the damage factor $D_2$ can be determined by experiment. To describe the law of residual strength under high strain rate, Hou et al. [63] proposed a new damage-softening statistical constitutive model by introducing a parameter [146]. The parameters $F_0$, $m$, $C_n$ and $E_d$ can be calculated by $V_f$ and $\dot{\varepsilon}$. The established model can well describe the damage evolution of concrete materials. Due to less parameters involved, the model can be utilized conveniently to describe the dynamic stress-strain relationship. However, The ZWT model is less commonly used in practical applications than the Holmquist-Johnson-Cook (HJC) model, which achieves a nice compromise between simplicity and computations accuracy for large-scale simulation, and has been utilized in LS-DYNA to simulate dynamic response of UHPC [69].

5.2. Holmquist-Johnson-Cook (HJC) model

5.2.1. The original HJC model and modifications

The HJC model was proposed by Holmquist et al. [148], which can well describe the crushing behavior of brittle materials under dynamic loading. It takes into account the effects of strain rate and damage accumulation and includes three aspects: yield surface equation, damage evolution equation and state equation. The detailed theory of the HJC model can be referred to the literature [148]. Du et al. [69]
Table 4

The ZTW model and modifications.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Damage variable</th>
<th>Constitutive model</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhu, Wang and</td>
<td>noneC₀</td>
<td>α = f₀(ε) + E₀  \int_0^\infty \left( \frac{1}{\theta_0} \right) \left( 1 - e^{-\frac{t - \tau}{\theta_0}} \right) dt + E₂  \int_0^\infty \left( \frac{1}{\theta_2} \right) \left( 1 - e^{-\frac{t - \tau}{\theta_2}} \right) dt</td>
<td>f₀(ε) = E₀t + \lambda^2 + \rho^2 t^2, λ and ρ are the elastic constants; t is time variable; τ is loading time; E₀ and θ₀ are the elastic modulus and relaxation time (low frequency Maxwell element); E₂ and θ₂ are those (high frequency Maxwell element). V₁ is the ultrasonic wave velocity after impact.</td>
</tr>
<tr>
<td>Tang [140]</td>
<td></td>
<td>quasi-static state</td>
<td></td>
</tr>
<tr>
<td>Lai et al. [43]</td>
<td></td>
<td>α = f₁(ε) + E₁  \int_0^\infty \left( \frac{1}{\theta_1} \right) \left( 1 - e^{-\frac{t - \tau}{\theta_1}} \right) dt</td>
<td></td>
</tr>
<tr>
<td>Zhang et al.</td>
<td></td>
<td>α = f₁(ε) + E₁  \int_0^\infty \left( \frac{1}{\theta_1} \right) \left( 1 - e^{-\frac{t - \tau}{\theta_1}} \right) dt</td>
<td></td>
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<tr>
<td>[147]</td>
<td></td>
<td>quasi-static state</td>
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<tr>
<td>Wang et al.</td>
<td></td>
<td>α = E₀  \int_0^\infty \left( \frac{1}{\theta_0} \right) \left( 1 - e^{-\frac{t - \tau}{\theta_0}} \right) dt</td>
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<tr>
<td>[73]</td>
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<tr>
<td>Hou et al.</td>
<td></td>
<td>α = E₀  \int_0^\infty \left( \frac{1}{\theta_0} \right) \left( 1 - e^{-\frac{t - \tau}{\theta_0}} \right) dt</td>
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<tr>
<td>[63]</td>
<td></td>
<td>quasi-static state</td>
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</table>

proposed an improved HJC model by considering the Lode-angle effect and strain rate effect of steel fiber. The modified failure surface equation was suggested as [149]:

\[ \sigma^* = [A(1 - D) + BP^*]R(\theta, \varepsilon)(m + n \ln \varepsilon) \leq S_{\text{max}} \]  

(7a)

\[ R(\theta, \varepsilon) = \frac{\frac{2}{1 - \varepsilon^2} \cos \theta + (2e - 1)\left[\frac{2}{1 - \varepsilon^2} \cos \theta + 5e^2 - 4e\right]}{4(1 - \varepsilon^2) \cos \theta + (1 - 2e^2)} \]  

(7b)

\[ \cos(3\theta) = \frac{3\sqrt{3} \varepsilon S_{\text{max}}}{2f^*} \]  

(7c)

\[ \varepsilon = 0.68 + 0.01P^* \]  

(7d)

where \( \sigma^* = \sigma/\sigma_{\text{f}} \) is the normalized equivalent stress, \( P^* = P/\sigma_{\text{f}} \) is the normalized pressure, \( f_{\text{f}} \) is the quasi-static uniaxial compressive strength; \( \varepsilon^* = \varepsilon/\varepsilon_{\text{f}} \) is the dimensionless strain rate, where \( \varepsilon_{\text{f}} \) is the reference strain rate; \( S_{\text{f}} \) is the deviatoric stress tensor and \( \varepsilon \) is a shape factor; \( J_2 \) is the second invariant of deviatoric stress; \( m \) and \( n \) are the strain rate sensitivity coefficients; \( \theta \) is the Lode-angle. \( A \) is the cohesion parameter; \( B \) is the pressure hardening coefficient; \( N \) is a pressure hardening exponent; \( C \) is the strain rate sensitivity coefficient; \( D \) represents the degree of damage; \( S_{\text{max}} \) is the maximum normalized stress. The function \( R \) only defined in the sector \( 0 < \theta < \pi/3 \), since the polar radius \( R(\theta, \varepsilon) \) extends to all polar directions \( 0 < h < 2\pi \) under threefold symmetry [150].

5.2.2. Determination of calculation parameters

The original parameters of HJC model are obtained under specific experimental conditions and have some limitations. Due to the complexity of the experiment to obtain the parameters, many researchers combine experiments and employ partially empirical values to determine HJC parameters. The HJC model was embedded in LS-DYNA to simulate the dynamic behavior of UHPC under high velocity ballistic impact in the authors’ previous work [151]. The HJC model parameters consist of four parts: basic material parameters, strength parameters, damage parameters and pressure parameters. A series of complex experiments are required to obtain these parameters exactly. Hence, some original parameters are adopted empirically and some materials properties are acquired according to the experimental data. In overall, the model shows excellent agreement with experimental results. Wu et al. [152] investigated the sensitivity of parameters and found that \( A, B, C \) and \( N \) were sensitive to the HJC model. It was found that \( A \) and \( B \) had a certain effect on the peak stress and peak strain of the stress-strain curve, and the influence of \( A \) on the peak stress was greater than the peak strain. Both \( C \) and \( N \) had certain influence on the peak strain of the stress-strain curve, but had little influence on the peak stress. Then, the sensitive parameters of HJC model were modified based on experimental results. The similar method was utilized to implement numerical simulation analysis in Ref. [153], and the obtained stress-strain curves exerted good consistency with the experimental data.

Due to higher compactness and lower crack propagation velocity, UHPC exerts different strain rate sensitivity under dynamic impact. The parameters of HJC model are originally proposed for normal strength concrete, which is a brittle material and does not consider the influences of steel fiber type and dosage. However, a suitable constitutive model with good parameter calibration is the key to obtain high fidelity simulation results [154]. The reasons mentioned above may result in low accuracy of numerical prediction results. Further investigations of the effects of fiber type, dosage and matrix strength on the parameters of HJC are required. Moreover, the existing researches mainly focus on the physical significance of HJC parameters, and an in-depth research on the experimental methods to obtain these parameters is recommended. In addition, coarse aggregates are being more and more utilized in UHPC. Their presence and interaction with other ingredients like fibers would strongly affect the fracture of UHPC and relevant modeling can be developed to build a more precise and deeper understanding of the dynamic performance of UHPC.

6. Dynamic failure pattern

6.1. Effect of strain rate

The failure pattern is an important response of UHPC under dynamic loading, which has close relationship with dynamic strength and energy absorption. The failure mechanism of NSC has been concentrated in most of the experimental studies [109,155–158]. However, the failure mechanisms of UHPC have been illustrated in very few studies. The failure mechanism can be divided into two categories, as illustrated in Fig. 15. For NSC, Cracks go through the ITZ around the aggregates under...
a low strain rate. Specimens break into several large fragments without crushing the aggregates. With the increase of strain rate, before the cracks have enough time to seek relatively weaker regions, the stress has increased sufficiently to fracture the coarse aggregates [157]. Multiple cracks are generated at higher strain rates so that the coarse aggregates are crushed into small pieces. However, for UHPC, the strengths of matrix and ITZ are significantly enhanced compared with NSC. Although cracking around the coarse aggregate is still the main failure pattern, some cracks across coarse aggregate begin to appear simultaneously, which shows differences from NSC [159, 160]. The difference in failure patterns results in higher energy dissipation and strength with the increasing strain rates. The failure patterns are referred to three categories under different strain rates: edge-cracks, fragmentation and pulverization [48].

6.2. Effect of steel fibers

The failure pattern of UHPC under quasi-static conditions is mainly controlled by steel fiber pull-out. With the increase of the strain rate, more and more steel fibers are fractured instead of pulled out [70, 160, 161]. Zhang et al. [53] investigated the dynamic failure pattern of UHPC with different content of steel fibers under a similar strain rate. It was observed that the plain UHPC was seriously disrupted under dynamic impact loading, UHPC with steel fibers content (1%, 2%, 3%) were broken into pieces, while UHPC with steel fibers contents (4%, 5%) kept essential integrity. The interlaced networks formed by randomly distributed steel fibers effectively prevented the matrix from breaking, which improved the impact resistance of the UHPC. Hence, the width and depth of the cracks decreased with the increase of steel fiber content. The bonding force between the matrix and steel fibers has important effect on dynamic failure patterns. Better bonding between the fiber and the concrete matrix declines the damage degree.

Ren et al. [38] investigated the dynamic failure pattern of UHPC with three volume fractions and two types of steel fibers. The typical failure patterns of UHPC with steel fibers at different strain rates are shown in Fig. 16. It was indicated that the damage degree of UHPC declined with the rising of steel fiber content. The conclusions agree well with the results in literature [43, 51, 53, 55, 63, 64]. As shown in Fig. 16, the micro-straight steel fiber had better crack resistance ability compared to the hooked ones. Su et al. [56] reported that with the increase of fiber length or aspect ratio, the impact resistance of UHPC was improved.

Wu et al. [59] investigated the failure pattern of UHPC with hybrid steel fiber. Their study attributed to the mutual effect associated with short and long fiber, UHPC with 1.5% LSF and 0.5% SSF showed the highest impact resistance. As illustrated in Fig. 17, in stage I, micro-cracks initiate at weak zones of concrete without steel fiber action. Short fibers can first prevent the formation of initiated micro-cracks in stage II. With the further increase of the load, the micro-crack develops into macro-cracks, and the short fibers are pulled out. In stage III, the long fibers begin to play a vital role in preventing crack development. Therefore, it needs more time and energy to crush the UHPC.

As illustrated above, in most of the reported studies, the failure mechanisms of concrete are mainly studied individually from ITZ, coarse aggregates and steel fibers. The addition of coarse aggregates in UHPC has significant effects on steel fibers distribution and interfacial bond, consequently affecting the failure pattern under impact loadings [86]. Therefore, it is essential to investigate the synergistic effect between coarse aggregates and steel fibres to better understand the failure pattern of UHPC system.

Due to the intensity and transitoriness of impacting UHPC, the failure modes are mainly studied in different stages and analyzed after the impact. The failure process of UHPC specimens during the SHPB tests can be captured by a high-speed camera [162–165], but the inner time-dependent failure progress of UHPC is still not clear. Numerical simulation can be utilized to describe the dynamic response of UHPC effectively. To simulate the failure process accurately under impact loading, cement matrix, aggregate, ITZ and steel fiber should be modelled, respectively. However, it is a complex problem that how to accurately obtain the mechanical parameters of concrete meso simulation and how to establish the relationship between meso and macro-scales. Moreover, the micro-cracks intrinsically existing during the fabrication of UHPC have an effect on the failure modes, which
should be considered in future study.

7. Conclusions and perspectives

Recently, increasing attention has been attracted to the dynamic characteristics of UHPC, reflected by the significance of academic research and engineering applications. The SHPB apparatus can be used to examine the dynamic properties under impact loading effectively. This paper reviews the applications of SHPB equipment to UHPC. The existing literature concerning experiments of UHPC investigated by SHPB are summarized and analyzed in detail. Based on the discussed topics, the following conclusions can be drawn:

(1) The SHPB is the most widely used device to characterize the dynamic compressive behaviour of UHPC and the strain rates of UHPC achieved by SHPB tests mainly range from 10 s\(^{-1}\) to 350 s\(^{-1}\). Pulse shaping technique and optimization of the aspect ratio of the specimens are the two essential methods to achieve the validity of the SHPB test. The proper thickness of the pulse shaper should be adopted to achieve constant strain rate and stress equilibrium. To minimize the influence of inertia effect and friction effect, the length to diameter ratio of specimen ranging from 0.5 to 1 is commonly adopted, and 0.4 is the recommended value.

(2) Based on the existing literature, a theoretical model is proposed by considering the strain rate and volume of steel fiber to predict dynamic strength. The micro-straight steel fibers have relatively better performance on enhancing the dynamic compressive strength of UHPC compared to the hooked ones. The larger aspect ratio results in a higher dynamic compressive strength. The maximum size of the coarse aggregate, the volume fraction of the coarse aggregate, the influence of the interaction between coarse aggregate and steel fiber on the dynamic characteristics need to be studied more systematically.

(3) Dynamic compressive strength increases with the reduced temperature. The peak strain at elevated temperature increases compared to room temperature. The elastic modulus decreases with the rising of strain rate under high temperatures from 200 °C to 800 °C. However, research on dynamic compressive properties under low temperature is limited, especially for UHPC, and some important factors such as degree of capillary saturation, pore size distribution and effects of freeze-thaw conditions that influence the dynamic characteristics of UHPC should be taken into account in future research.

(4) The types of steel fiber have little effect on the peak strain of UHPC. Because of the higher elastic modulus of the coarse aggregate, the peak strain decreases with the increase of the maximum size of coarse aggregate. The dynamic elastic modulus increases with the rising of strain rate. The content of steel fibers has no significant influence on the dynamic elastic modulus of UHPC. The consistent conclusions on the distributions of peak strain for UHPC with the changing strain rate and steel fibers are not reached.

(5) The dynamic increase factor (DIF) of UHPC improves with the increase of strain rate while decreases with the rising of steel fiber content. The transition strain rate can reflect the strain rate sensitivity and the transition strain rate of UHPC is larger than NSC. With the increase of the steel fibers content, the transition strain rate of UHPC increases. It is essential to quantitatively describe the lateral inertial effect and the real strain rate effect on DIF. The energy absorption of UHPC is significantly larger than that of HSC and NSC. The energy absorption ability is proportional to the strain rate and steel fiber content. Based on the existing data, a prediction model of energy absorption is proposed.

(6) The ZWT model and HJC model are the commonly used dynamic constitutive models and their modifications are applicable for UHPC. The modified ZWT and HJC models all exert good consistency with the experimental results. However, the excessive number of parameters leads to great difficulty in the calculation, which brings inconvenience to the application of the model. Nowadays, the relevant parameters of ZWT model are generally obtained by fitting the experimental data and the damage factor \(D\) is utilized to quantify the damage degree of UHPC. The HJC model has been implanted in LS-DYNA to simulate dynamic behaviour under compression and shows a good performance. However, more attention should be paid to the experimental methods to obtain reliable HJC parameters.

(7) A new failure mechanism of UHPC under different strain rates is proposed. Under a low strain rate, cracking around the coarse aggregate is still the main failure pattern, some cracks across coarse aggregate begin to appear simultaneously. The damage degree increases with the increase of strain rate while decreases with the rising of steel fiber content. The width and depth of the cracks have a noticeable decline with the increasing steel fibers. The damage resistance of UHPC is increased with the increase of fiber length or aspect ratio. Additionally, the effect of initial cracks and the synergistic effect between coarse aggregates and steel fibers of UHPC on the dynamic failure pattern should be considered in future research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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